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ANTI-UAV DEFENSE REQUIREMENTS FOR GROUND FORCES AND HYPERVELOCITY ROCKET LETHALITY MODELS

by

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This thesis analyzes the threat that unmanned aerial vehicles (UAVs) pose to U.S. ground forces. The operational environment in which both lethal and non-lethal UAVs may be encountered by friendly surface forces is examined to determine the elements of UAV operation which may be exploited in defense against UAVs. Two probability models of the air defense endgame are developed to examine the potential lethality of hypervelocity rocket anti-UAV weapons. These models are used to determine the detonation distance which maximizes the probability that a single hypervelocity rocket kills a UAV. Data used in this study are synthetic to prevent disclosure of classifiied and proprietary information and allow wider distribution of this thesis.

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and
Hypervelocity Rocket Lethality Models

by

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ABSTRACT

This thesis analyzes the threat that unmanned aerial vehicles (UAVs) pose to U.S. ground forces. The operational environment in which both lethal and non-lethal UAVs may be encountered by friendly surface forces is examined to determine the elements of UAV operation which may be exploited in defense against UAVs. Two probability models of the air defense endgame are developed to examine the potential lethality of hypervelocity rocket anti-UAV weapons. These models are used to determine the detonation distance which maximizes the probability that a single hypervelocity rocket kills a UAV. Data used in this study are synthetic to prevent disclosure of classified and proprietary information and allow wider distribution of this thesis.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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I. INTRODUCTION

A. UNMANNED AERIAL VEHICLES (UAVs) AS AN ASSET

The Joint Chiefs of Staff define an *unmanned aerial vehicle (UAV)* as:

> a powered, aerial vehicle that does not carry a human operator, uses aerodynamic forces to provide vehicle lift, can fly autonomously or be piloted remotely, can be expendable or recoverable, and carry a lethal or non-lethal payload. Also called UAV. Ballistic or semi-ballistic vehicles, cruise missiles, and artillery projectiles are not considered. (JCS, 1991, p. GL-4)

UAVs offer advantages in place of, or supplementing, manned aircraft. The advantages include low cost, payload modularity, high endurance, and reduced personnel susceptibility.

Warfare has changed significantly since World War II. Modern technology allows combat units to effectively fight at long range day or night, even during adverse weather. Improved mobility of surface forces, on land or sea, and significant advances in aircraft capability have driven the design, acquisition, and fielding of accurate long range weapons. In many instances, the accuracy of modern weapons has exceeded the precision targeting capability of surface units. Sensors such as space-based reconnaissance satellites are extremely expensive, over-tasked, and often do not provide real-time imagery required for targeting data. UAVs have

assumed a significant role in airborne reconnaissance. UAVs are especially attractive because they minimize risk to personnel and allow more capable manned aircraft to focus on other missions. In light of impending defense cuts, UAVs become even more attractive since they offer a low cost alternative to manned aircraft or satellites. Reconnaissance is the primary mission of most UAVs. However, UAVs are also designed to perform lethal missions such as suppression of enemy air defenses and anti-radiation attack. The early stages of the war with Iraq demonstrated that lethal UAVs increase overall force effectiveness when used to supplement manned strike missions. As U.S. forces are reduced in response to the break-up of the Soviet Union and Warsaw Pact, relatively low cost lethal UAVs, performing high risk missions, become more important as military forces face demanding missions with fewer personnel and less equipment. UAVs are effective force multipliers which allow the military to "do more with less."

B. UAVs AS A THREAT

The obvious advantages of UAVs for U.S. forces also apply to foreign militaries. The U.S. has never fought an enemy who employed UAVs. However, it is likely that U.S. forces will have to defend against UAVs in future conflicts. Analysis has been done to understand the capabilities and effectiveness of UAVs. However, much less work has been done to study the

susceptibility and vulnerability of U.S. forces to hostile UAVs. The ability of U.S. forces to defeat enemy UAVs should be addressed.

C. UAV SURVIVABILITY

Survivability analyses performed for the U.S. Army's Aquila UAV program and the Joint Short Range UAV program provide insight to anti-UAV capabilities and requirements. The Center for Naval Analyses, Army Missile Command, and Naval Air Development Center have performed survivability, vulnerability, and susceptibility evaluations of various UAV systems. These studies have used simulations to evaluate the effectiveness of guns and missiles against U.S. UAVs. As discussed in the Center for Naval Analyses' *Joint UAV Phase I Cost and Operational Effectiveness Analysis (U)*, it is essential to study possible threats to the entire UAV system, including the ground-based support elements. Both current and future threats are considered to ensure the UAV system retains survivability as developmental weapons become operational. Survivability studies may also reveal the requirement for new air defense weapon systems if current anti-UAV capabilities are inadequate. The most prevalent threats to airborne UAVs are guns, rockets, and electro-optical, infrared, and radar-guided missiles. Although designed to study the characteristics of UAVs, survivability studies discuss the

limitations and capabilities of both ground- and air-launched weapon systems which may be tasked to defend against UAVs.

Survivability studies include estimates and measurements of UAV visual, infrared, radar, and aural signatures. These data are essential for thorough evaluation of sensor capabilities against UAV targets.

In addition to UAV survivability studies, the *Joint Tactics, Techniques and Procedures For Unmanned Aerial Vehicles (UAV)* manual also provides references to classified documents which discuss threats to UAVs (JCS, 1991, p. II-5). The system threat assessment reports for the close range, medium range, and endurance UAVs being developed by the Joint UAV Program Office discuss the impact of generalized threats and the characteristics of specific threats to these UAVs.

UAV survivability studies also provide insight into the problem of defending against UAVs. Target susceptibility and vulnerability assessments are essential to design of any air defense weapon system. Studies which provide recommended employment tactics also give the anti-UAV weapon designer an understanding of where, how, and when an efficient operator will employ his UAV assets. Using the models, simulations, and information presented in UAV survivability and threat assessment studies will accelerate the development of new anti-UAV weapons and maximize the anti-UAV effectiveness of existing systems.

D. ANTI-UAV CAPABILITIES

Consolidation of information regarding UAV capabilities and the operational environment in which they are employed provides an understanding of the requirement for an anti-UAV capability for ground forces. The anti-UAV weapon system envisioned by the U.S. Army Missile Command, Advanced Systems Concepts Office incorporates an acquisition sensor module and a killer module. A sensor system screening was performed in 1991. Information related to some candidate destruction mechanisms is discussed in classified UAV survivability studies. Hypervelocity rockets also present a viable anti-UAV capability, not considered in previous UAV survivability studies, that may offer a more lethal or cost effective kill mechanism than systems currently in the U.S. air defense weapon inventory.

E. OUTLINE

Chapter II provides an overview of UAV capabilities for those readers who are unfamiliar with UAV technology and operations. The recent history of UAVs is discussed with emphasis on the effectiveness of UAVs in conflicts of the last decade. UAV mission descriptions are described providing the reader an understanding of the combat power of both lethal and non-lethal UAVs. The various UAV system configurations and payload options are described and representative systems are provided. The land combat employment concepts for UAVs on the

non-linear battlefield are discussed since this thesis focusses on the threat that UAV pose to U.S. ground forces.

Chapter III analyzes the combat environment in which UAVs are likely to be encountered. The phases of UAV operation are examined to understand how UAVs and their support equipment may be defeated. Issues related to anti-UAV defense including current sensor capabilities are discussed.

Chapter IV introduces the concept of using hypervelocity rockets for air defense. A lethality model based on a cookie-cutter damage function is developed from the engagement geometry. The measure of effectiveness analyzed is the probability that at least one hypervelocity rocket penetrator impacts the UAV's vulnerable area. The fuzing of the rocket is examined to determine how the rocket's effectiveness against UAVs may be maximized. The model may be adapted to consider the requirement for multiple hits. The model assumptions are examined for appropriateness and a sensitivity analysis with respect to the estimate of the UAV size is performed.

Chapter V relaxes restrictive assumptions of the cookie-cutter model and develops a more detailed model based on the diffuse Gaussian damage function. This model allows for study of targets which have vulnerable components separated by some distance. The rocket fuzing is optimized to provide the maximum probability of destroying the target. Again, sensitivity to UAV vulnerable area estimate errors is examined

revealing that a biased estimate of UAV vulnerable area is appropriate to provide a more robust rocket fuzing algorithm.

Chapter VI summarizes this thesis. Major conclusions are addressed. Ways in which the models presented may be used are proposed. Finally, areas of future study are addressed.

II. UAV OVERVIEW

A. HISTORY

Technological advances of recent decades have drastically broadened UAV capabilities. Current technology allows production of unmanned systems that are controllable by human operators from long distances, or that operate autonomously. Future unmanned systems will become even more capable at performing battlefield reconnaissance and lethal attack missions. Eighteen nations have already used UAVs in non-target roles indicating that UAVs are likely to be part of future combat of any intensity.

UAVs were used to defeat ground forces with great success in two recent conflicts. Israeli forces used Mastiff, Scout, and Samson UAVs as decoy and reconnaissance vehicles to prepare for and perform an attack against Lebanon in 1982. UAVs mimicked electronic signals typical of Israeli jets and relayed the location of responding Syrian anti-aircraft radars to an airborne E-2 Hawkeye. F-4 Wild Weasel anti-radiation missile carrying aircraft, controlled by the E-2, destroyed numerous Syrian surface-to-air missile sites in the Bekaa Valley in just one day. The Israelis sustained minimal manned aircraft losses while destroying more than 90 hostile aircraft (Edwards, 1990, p. 8). It is significant to note that the

U.S. lost three aircraft to anti-aircraft fire while attacking Syrian positions without UAVs in 1983 (Shaker and Wise, 1988, p. 100).

The U.S. Army, Marine Corps, and Navy flew 522 UAV sorties totaling 1641 hours during combat operations against Iraq in 1990-91. At least one UAV was airborne at all times during the operation and the Navy reported that "UAVs performed superbly during Desert Shield/Storm" (Green, 1991, p. 8). The Pioneer UAV was used to provide real-time battle damage assessment, artillery and naval gunfire spotting/adjustment, reconnaissance, advanced warning, and coordination of ground and air operations. The French Alpilles Mini Avion de Reconnaissance Telepilote (MART) UAV was also used for reconnaissance and surveillance in support of coalition forces.

Information collected by BQM-147A Exdrone UAVs allowed Marine Corps ground units to move into Kuwait earlier than expected. Ground launched BQM-47C Chukar target drones were used in conjunction with Tactical Air Launched Decoys (TALD) deployed from Navy and Marine aircraft to induce Iraqi units to activate air defense radars. F-4 Wild Weasel aircraft launched anti-radiation missiles to destroy the exposed radar sites. These systems contributed significantly to successful suppression of Iraqi air defenses during air strikes. These air strikes effectively weakened Iraqi forces prior to ground

engagement (Lovece, 1991, p.11). These examples demonstrate the significant threat that UAVs pose to ground forces.

B. MISSION DESCRIPTION

1. Range and Endurance

UAVs of various range and endurance capabilities threaten ground forces at all levels. Figure 1 shows the Department of Defense approved UAV class categories (JCS, 1991, p. I-3). Close range UAV systems will service lower echelon tactical units, possibly of division size or smaller. They give the enemy commander a view of the disposition of both friendly and hostile forces within and beyond his weapons range. Medium range UAV systems may be used to provide near real-time reconnaissance data required for pre- and post-strike planning for manned aircraft missions. They may also be used as decoys or target designation vehicles to reduce the susceptibility of manned aircraft while performing high risk missions against U.S. forces. An enemy corps or theater-level commander may utilize a high endurance UAV to provide wide area surveillance of U.S. ground units and early warning of U.S. advances. The information obtained from such a high endurance UAV, fused with information obtained by shorter range UAVs (controlled by enemy tactical units) and other sensors, will provide the enemy commander an in-depth perspective of combat progression, which may allow valuable anticipation of U.S. maneuvers.

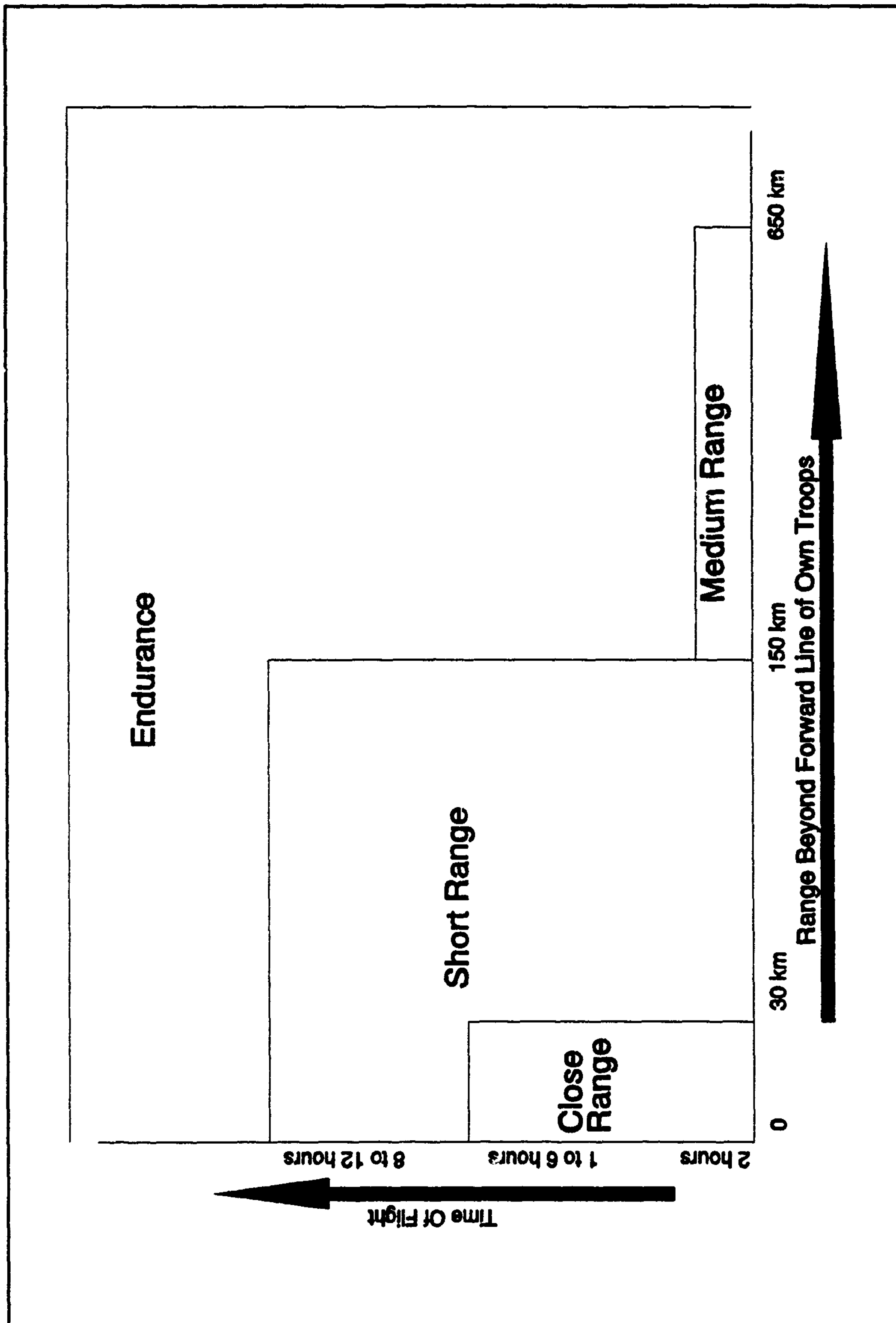

Figure 1 DOD Approved UAV Class Categories

UAVs may provide opposing forces with theater reconnaissance capability comparable to that of U.S. assets (Dale, 1991, pp. 34-36). For example, they may be used for temporary coverage comparable to that of reconnaissance satellites. The Condor UAV is designed to fly at 65,000 feet with an endurance of more than 120 hours and has the potential to serve as a relatively inexpensive substitute for satellite surveillance and early warning systems (Tice, 1991, p. 47).

2. Missions Utilizing Non-lethal UAVs

UAVs need not be capable of delivering weapons to be of value. Enemy non-lethal UAVs may collect information about the battlefield and U.S. forces, direct weapons to their target, or assess damage. Some non-lethal missions are:

- artillery or naval gunfire support
- battle damage assessment
- defense saturation
- decoy
- airborne surveillance for search and rescue
- route and landing zone reconnaissance support
- sonobuoy delivery
- nuclear, biological, or chemical weapon usage detection
- meteorological observation
- minefield detection or clearing
- electronic warfare
- communication relay.

The primary worth of non-lethal UAVs is their capability to provide high-resolution imagery of the battlefield. This information is extremely valuable because it provides the targeting data and identification required for effective long range attack. This feature will greatly increase the lethality of the battlefield because enemy commanders will be able to acquire information about U.S. forces, fuse information from multiple sources, and distribute information on a real-time or near real-time basis. These factors will allow engagement of high value targets at long distances with exceptional accuracy. The real-time reconnaissance capability of UAVs provides battlefield commanders accurate information in time to influence their decisions and make combat operations more effective. Thus, detection and attack of U.S. units becomes effective well beyond direct fire range.

3. Usage of Lethal UAVs

Lethal UAVs are those configured to deliver ordnance or be guided as "kamikaze" weapons. The distinction between modern missiles and lethal UAVs is blurred at best. However, a useful distinction is that missiles are typically designed for one-time use. Lethal UAVs may possibly be recovered and reused if they do not find a suitable target.

An example of a lethal UAV is the Tacit Rainbow emitter attack weapon, which was under development for the

U.S. Air Force. This system can fly autonomously; loiter in a predetermined area; and then detect, classify, and attack active emitters (Libbey and Putignano, 1990, p. 42). The German Dornier DAR UAV also performs anti-radar missions autonomously in a pre-programmed search area. Lethal UAVs provide a cost effective means of decreasing the susceptibility of costly close support aircraft (Karch, 1990, p. 47). Some lethal UAV missions are:

- anti-radiation attack
- suppression of enemy air defenses
- vehicle attack
- mine laying/torpedo delivery
- air defense.

C. SYSTEM OPTIONS

1. Configurations

UAVs may be classified by configuration: lighter-than-air, rotary, fixed-wing propeller, or jet. Each configuration has advantages and disadvantages as shown in Table I.

a. Lighter-Than-Air

Lighter-than-air UAVs are especially well-suited for long endurance surveillance and early warning missions. High altitude capability allows onboard sensors to provide over-the-horizon detection. Look-down viewing aspect from enemy UAVs may also allow detection of low-flying U.S.

TABLE I UAV CONFIGURATION ADVANTAGES AND DISADVANTAGES

Configuration	Advantages	Disadvantages
Lighter-Than-Air	long endurance high altitude capability low maintenance	slow speed poor maneuverability high vulnerability
Rotary	vertical take-off and landing maneuverability ability to hover	maintenance intensive slow speed not aircraft launchable
Non-Rotary VTOL	vertical take-off and landing high maneuverability ability to hover higher speeds	limited technology base
Fixed-Wing Prop	long endurance higher speeds flexible payloads	difficult shipboard recovery launch/recovery system required
Fixed-Wing Jet	high speed long range	higher cost high tech maintenance high IR signature high aural signature

aircraft normally obscured by surface clutter. The U.S. Air Force Seek-Sky-Hook aerostat program provides radar coverage in the Florida Straits to guard against air incursions from Cuba (Shaker and Wise, 1988, p. 116). The U.S. Customs Service and Coast Guard use tethered aerostats for drug interdiction and law enforcement operations. As U.S. drug interdiction operations become more effective, smugglers may utilize UAVs to detect and avoid U.S. law enforcement forces.

b. Rotary

Rotary UAVs provide significant launch and recovery advantages. No external equipment is needed and minimum area is required for vertical takeoff and landing.

All-weather launch and recovery capability is possible using systems similar to the Canadian BEARTRAP or U.S. RAST used to position, launch, and recover manned helicopters onboard ships in high sea states. The Canadian CL-227 Sentinel UAV utilizes such a system (Shaker and Wise, 1988, p. 107). Rotary systems typically require more maintenance time due to the dynamic components inherent in rotor systems, but are less likely to be damaged during recovery. The standard shipboard recovery method for fixed-wing UAVs is to fly them into a net which usually causes structural damage (Davis, 1991, p. 23). Rotary UAVs are difficult to launch from aircraft. However, rotary systems are especially well-suited for shipboard operations.

c. *Non-Rotary VTOL*

Non-rotary VTOL (vertical takeoff and landing) UAVs offer the maneuverability and takeoff/landing advantages of rotary UAVs yet allow greater speed. Some advanced designs allow high subsonic speed capability. Shrouded fan designs have been explored by Sandia National Laboratories for the U.S. Marine Corps (Shaker and Wise, 1988, pp. 113-114). This system, Airborne Remotely Operated Device (AROD), may incorporate a fiber optic cable link to transmit video camera images from the UAV to an operator's heads-up display. The system may also carry hypervelocity rockets to be fired downward at armored vehicles thereby increasing the probability of damage, since these targets are more vulnerable

topside. This type of UAV remains relatively undeveloped and it is unlikely that U.S. forces will encounter them as opposition.

d. *Fixed-Wing Propeller*

The majority of operational UAVs are fixed-wing propeller-driven aircraft. These have a relatively simple design, long range, high reliability, high endurance, payload modularity, multiple launch options, and low cost. The engine size required to power these aircraft allows them to remain very light. This, combined with composite material advances, makes these systems capable of carrying a wide array of sensors or weapons. Such systems can be launched by hand, railed launchers, jet assist, or aircraft drop. This is the most common UAV type and is likely to remain so because of low cost and wide availability. U.S. forces will probably encounter enemy UAVs of this type.

e. *Fixed-Wing Jet*

Fixed-wing jet-powered UAVs offer significant speed and power advantages. Additional power from jet propulsion allows the UAV to carry more fuel, sensors, or weapons than propeller-driven UAVs. A jet UAV is typically less expensive to build than a manned jet aircraft; the absence of crew support systems alone represents substantial savings. Such UAVs were used extensively by the U.S. during the Vietnam war (Miller, 1988, pp. 15-19). The relatively

high cost of jet engines makes these UAVs significantly more expensive than other types. Jet engines also provide a larger infrared signature than lower performance engines, and the stronger airframes required to support the additional weight of jet engines may provide a larger radar cross section, increasing detectability. Stealth technology offers greater survivability but may also overwhelmingly increase the UAV cost. It is also unlikely that forces opposing the U.S. will have stealth technology available for the design of aircraft in the near-term. If the speed of a jet is required, a UAV may be used to avoid the risk of human life and scarce manned aircraft in a hazardous mission such as suppression of enemy air defenses.

2. Payloads

a. Non-lethal Sensors

UAV sensors include video or still cameras, low-light television, forward-looking infrared (FLIR), laser range finders, infrared line scanners, signals intelligence or electronic counter measure devices, radar, and meteorological or nuclear-biological-chemical agent measuring devices. A single UAV may carry multiple sensors, or interchangeable sensor modules. Meteorological conditions such as cloud cover, humidity, and temperature significantly impact sensor effectiveness. Numerous sensors are available for various missions and weather conditions.

b. *Lethal Weapons*

Enemy UAV weapons may be tailored for specific missions. The simplest design may consist of a model airplane loaded with plastic explosives flown by remote control to attack soft targets; such might be well-suited for surgical strikes by special operations or terrorist units. The other end of the design spectrum may be represented by "mini-bomber" UAVs delivering smart munitions as do modern strike aircraft (Dugdale, 1987, p. 127). Developmental Sciences' Skyeye UAV design incorporates four wing load stations which can carry 2.75 inch ground attack rockets, deployable jamming modules, and perhaps even Stinger missiles (*Aviation Week and Space Technology*, 1986, pp. 68-83). It is likely that U.S. forces will not encounter such highly sophisticated systems. Lethal UAVs like the U.S. Tacit Rainbow or Israeli Harpy are capable of long loiter and autonomous firing for continuous suppression of enemy air defenses (SEAD). Without these UAVs, SEAD operations cannot be performed continuously. SEAD is often performed only prior to major air strikes, alerting the enemy to an impending attack (Kelleher, 1988, p. 46).

3. Communications and Control

Reliable communication with a remote operator is essential to mission success for many UAVs. UAV command uplink, status downlink, and data link utilize radio transmissions in the 20-1800 Mhz range. These communications

may be encrypted for security. Short range systems may also use fiber optic cable links (Culver and Smith, 1991, pp. 24-30). Some UAVs incorporate autonomous modes which do not require any communication.

D. DETECTABILITY

1. Optical/Visual

UAVs are substantially smaller than manned aircraft, making them relatively difficult to detect with optical sensors. Visual detectability of an aircraft is dependent upon an optical difference between the aircraft and its background. In comparison with manned aircraft properties, UAV luminance contrast with the background is minimal due to the absence of lighting, reduced exhaust glow from small engines, and less surface reflection. Reduced luminance contrast increases the importance of chromatic contrast. Tactical paint schemes may be used to camouflage a silhouette enhanced by chromatic contrast. It has been determined that blue/gray colored UAVs are less susceptible to electro-optical missiles than are green colored UAVs.

2. Infrared

The light weight of a typical UAV allows the use of small engines, which produce a relatively weak infrared (IR) signature. The IR signature may be reduced by ducting exhaust through the propeller or rotor wash to quickly dissipate hot gases. Similar systems have been used on U.S. helicopters.

IR jammers have also been deployed on U.S. helicopters; miniaturization of such jammers may be possible, allowing their use on UAVs.

3. Radar

Metal skins of conventional manned aircraft produce a relatively large radar cross section. Stealth designs are available to reduce radar cross section, but are costly. Many UAVs are constructed with composite materials which do not reflect radar. Radar penetrates much of the UAV surface but may partially reflect off internal equipment. Radar cross section may be reduced by use of radar absorbing materials. Developmental Sciences' Skyeye UAV incorporates eight pounds of radar absorbing material, yielding a side aspect radar cross section of less than 0.15 m^2 (*Aviation Week and Space Technology*, 1986, pp. 68-83). Radar cross sections of future UAVs may be as small as 0.001 m^2 with the use of composite materials and radar absorbing materials. On the other hand, simple devices which increase radar cross section allow UAVs to successfully function as decoys imitating larger aircraft.

4. Acoustic

The engines for many non-jet UAVs are small enough to allow the use of a sound muffler, thereby reducing acoustic detectability. Limited research has been done to investigate the feasibility of detecting or tracking aircraft with acoustic devices. Battlefield noise may make reliable and

predictable aural detection of UAVs very difficult. However, since UAVs do not have the characteristically large infrared and radar signatures of manned aircraft, use of acoustic systems warrants consideration. Acoustic sensors may allow U.S. ground forces to passively search for UAVs, reducing the probability of counter-detection. Modification of existing acoustic detection systems or development of new systems may provide a reliable method of detecting UAVs.

E. REPRESENTATIVE SYSTEMS

Tables II and III profile representatives of major UAV configurations. These characteristics provide typical performance parameters for different configurations.

F. LAND COMBAT EMPLOYMENT CONCEPTS

Battlefield commanders now influence a much larger area than they did in the past because of increased weapons' range, accuracy, and mobility. Modern warfare is not tied to head-on confrontation. Advanced systems provide enemy forces the capability to attack U.S. forces' weak points at opportune times and locations (Forster, 1991, p. 15). UAVs can serve as sensors to fill gaps between widely dispersed, highly mobile units.

UAVs may enable opposing units to efficiently search for and locate U.S. forces. UAVs provide time critical information required to successfully attack far beyond the

TABLE II REPRESENTATIVE FIXED-WING UAV SYSTEMS

Fixed-Wing Propeller

Name:	Pioneer 1 (USN, USMC)
Manufacturer:	AAI (US), Mazlat (Israel)
Powerplant:	26 hp air cooled piston
Weight:	400 lb
Payload:	100 lb
Height:	3.3 ft
Length:	14 ft
Wing Span:	16.9 ft
Endurance:	6-9 hrs
Ceiling:	15000 ft
Cruise speed:	48-70 mph (Max 106 mph)
Maximum Range:	100 miles
Sensors:	video, FLIR, ESM, laser range finder
Notes:	1) high winged fiberglass and metal monoplane
	2) rear mounted engine
	3) remote control operation
	4) launched takeoff or runway running takeoff
	5) net recovery or runway landing

Fixed-Wing Jet (Lethal Capability)

Name:	NV-144
Manufacturer:	Northrop (US)
Powerplant:	turbojet
Weight:	1,500 lb
Payload:	300 lb
Wing Span:	10.7 ft
Length:	19.6 ft
Width:	1.7 ft
Endurance:	2.75 hrs
Ceiling:	52,500 ft
Top speed:	668 mph
Maximum Range:	1,105 miles
Sensors:	ESM, Weather sensors, video
Special missions:	ordnance delivery and jamming
Notes:	1) cantilever high-wing monoplane
	2) air, land or ship launch
	3) parachute recovery
	4) pre-programmed or remotely controlled

forward line of one's own troops. It is likely that these systems will be relatively simple, require minimal training, and not detract from other tasks. For lower-level tactical operations, UAVs may be deployed in large numbers.

Enemy UAVs may disrupt U.S. operations by locating and/or attacking command posts, air defenses, communications equipment, and logistics centers. Lethal UAVs may effectively

TABLE III REPRESENTATIVE NON-FIXED-WING UAV SYSTEMS

Lighter-Than-Air

Name:	Model 500 Aero-ship
Manufacturer:	FUJI (Japan)
Powerplant:	two 1.3 hp air cooled engines
Weight:	41 lb
Length:	26 ft
Wing Span:	10.7 ft
Ceiling:	3,280 ft
Max speed:	50 mph
Sensors:	video and others

Rotary

Name:	CL-227 Sentinel (Canadian Navy)
Manufacturer:	Candair (Canada)
Powerplant:	50 hp gas turbine
Weight:	340 lb
Payload:	60 lb
Height:	5.4 ft
Body Width:	2.1 ft
Rotor Arc:	8.3 ft
Endurance:	4 hrs
Ceiling:	9,200 ft
Top speed:	80+ mph
Maximum Range:	30+ miles
Sensors:	video, audio, IR, radar
Notes:	1) contrarotating 3 blade propellers 2) remote control operation 3) automated shipboard recovery system

Non-Rotary VTOL

Name:	SHORTS SKYSPY
Manufacturer:	Short Brothers PLC (UK)
Powerplant:	65 hp two stroke inline
Weight:	286 lb
Payload:	44 lb
Height:	4.5 ft
Body Width:	3.6 ft
Fan Diameter:	2.8 ft
Endurance:	1.5 hrs
Ceiling:	6,000 ft
Top speed:	118 mph
Sensors:	video and others
Notes:	1) remotely controlled ducted fan VTOL 2) secure data link

locate U.S. forces and attack autonomously, allowing enemy personnel to concentrate on other tasks. UAVs provide reconnaissance and battle damage assessment information required to deliver effective long range weapons and conduct re-attacks. Intelligence data collected by UAVs provides the

battlefield commander timely knowledge of the threat and an appreciation of the relative combat power of the opposing force (Coghlan, 1989, p. 59). This capability should provide the UAV user some control over the location and tempo of battle.

III. OPERATIONAL ENVIRONMENT

A. UAV OPERATIONS

UAVs have varying potential to inflict damage on ground forces that is dependent on configuration, control mechanism, mission, and environment. An effective anti-UAV system must be able to counter threats at various levels of the UAV capability spectrum. Examination of UAV operations yields a thorough representation of the threat presented by UAVs. Such an analysis assesses the information and performance capabilities required for successful anti-UAV operations.

All UAV missions, both lethal and non-lethal, are characterized by some combination of the following phases of operation: launch and recovery, transit, search and surveillance, data transfer, and attack. Examination of UAV performance capabilities during each phase reveals system elements which have vulnerabilities exploitable by ground forces defending against UAVs.

1. Launch and Recovery

UAV missions begin with the launch phase. Detection during this phase is very difficult. Launch of long range UAVs typically occurs far behind the forward line of troops, while launch of close and short range UAVs may occur from almost any point on the battlefield. Ground support

facilities for remotely-piloted UAVs are often collocated with the launch site. Successful attack of UAV control facilities will significantly degrade UAVs under remote-control operation. Ground-based elements of UAV operations are not hardened and are vulnerable to attack by artillery, surface-to-surface missiles, and ground-attack aircraft. Detection of UAV launch and recovery operations or storage facilities may allow destruction of UAV support equipment and information processing stations. If UAV operations are perceived to be having a major impact on a battle, ground-based elements of UAV operations may become primary targets for ground-attack aircraft. Location and destruction of UAV storage and basing facilities will significantly degrade enemy reconnaissance and attack capabilities. However, autonomous UAVs do not require a control facility; their launch site is usually very mobile. In fact, many U.S. lethal UAVs are launched from fighter or attack aircraft.

2. Transit

Once remotely controlled UAVs are airborne, command uplink and status or data downlink may be detectable or jammable. However, this is not a completely reliable means of detecting or defeating UAVs. UAV guidance may be provided by pre-programmed flight path or tethered link not requiring detectable radio frequency transmissions. For example, a fiber optic cable control link is employed in the AROD UAV.

Remote-controlled UAVs may also be pre-programmed to fly a specific mission profile in the event of control link jamming or malfunction. The Skyeye UAV circles while increasing altitude for a predetermined time, then flies the last known recovery course in the event of lost data link (*Aviation Week and Space Technology*, 1986, pp. 68-83). UAVs may be controlled by mixed remote and pre-programmed guidance as is done in the Belgian Epervier system. As shown in Figure 2, the Epervier is visually guided at take-off, remotely controlled by radio during transit to and from the surveillance area, and guided by a pre-programmed course during surveillance (*Jane's Battlefield Surveillance Systems 1990-91*, 1990, p. 176). Thus, control link transmissions may be detectable or susceptible to jamming during some part of a hostile UAV flight or not at all.

UAVs present smaller signatures and vulnerable areas than manned aircraft under the same scenario. However, scenario conditions may be very different. UAVs need to skirt terrain profiles more widely than do manned aircraft because the absence of a human aircrew reduces terrain avoidance capability (Dean, 1990). UAVs typically do not possess any evasive maneuvering capability and often fly at relatively slow airspeeds. Also, UAVs may need to fly closer to targets than do manned aircraft to be effective. These factors may tend to make UAVs more susceptible to air defenses than comparable manned aircraft.

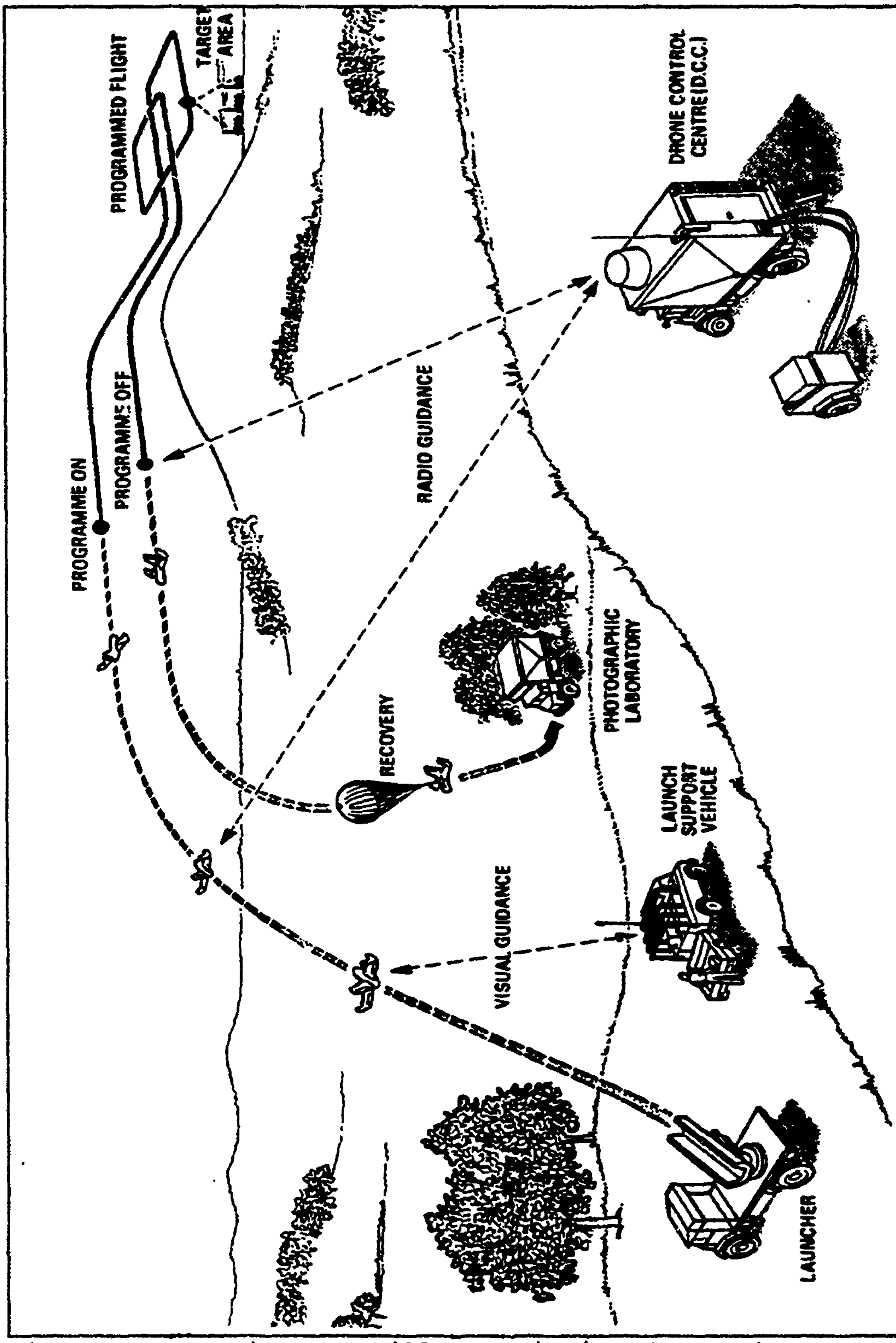

Figure 2 Epervier Surveillance Mission (Jane's)

3. Search and Surveillance

UAV sensor capabilities influence the threat to ground forces. The maximum distance at which a UAV can endanger ground forces is considered the keep-out range. Obviously, the keep-out range or susceptibility of ground forces increases as UAV sensor effective range increases. However, increasing UAV sensor range involves weight and cost compromises which must be considered in the analysis of the UAV threat.

a. *Optical Sensors*

Optical sensor systems are the type most commonly employed on UAVs. This technology is well developed and light weight, high-resolution video equipment is readily available and relatively inexpensive. The major drawbacks to optical sensors are their environmentally limited range and narrow instantaneous field-of-view. These features tend to limit surveillance capability and increase search times. The primary advantage of optical systems is the capability for positive visual identification of targets, which is necessary to avoid friendly-fire casualties. Low-light television technology allows night operation. UAV optical sensors are capable of making detection of typical battlefield targets at a range of approximately 1.5 kilometers. (Dynetics, 1991, pp. 6-1 - 6-20)

b. *Forward-looking Infrared Sensors*

Forward-looking infrared (FLIR) technology has greatly increased night fighting effectiveness. FLIRs allow detection with relatively wide fields-of-view, thereby increasing UAV search area and decreasing search time compared to those of an optical sensor. Battlefield targets often have an infrared signature more detectable than their visual signature since camouflage techniques can effectively defeat optical sensors. As is true of optical sensors, FLIR system effectiveness is highly dependent on environmental factors such as haze, humidity, and temperature. UAV wide field-of-view FLIR sensors are capable of detecting battlefield targets at a range of approximately 3 kilometers. (Dynetics, 1991, p. 4-17)

c. *Radio Frequency Intercept Sensors*

Radio frequency intercept (RFI) systems provide a passive sensor capability which does not require the UAV to actually "see" the target. Electronic emissions are detectable by relatively unsophisticated devices which provide accurate bearing information. They allow detection of active sensors at a much greater range than the active system's effective range. RFI systems offer all-weather, day/night capability since they are less dependent on the environment than are other passive sensors. RFI provides bearing-only information, and significant search times may be required to

localize an intermittent mobile target. However, RFI provides a means of cuing visual sensors (Roy, 1991). This sensor type is well-suited for a high endurance, autonomous, lethal anti-radiation UAV. A computer library of emitter characteristics may allow classification of targets to facilitate prioritized target selection. A major limitation of RFI sensors is that they provide no capability to detect electronically passive targets.

d. *Laser Range Finders*

All passive sensors share the inability to provide precise instantaneous target location information. When terrain is relatively uniform, information from ground or satellite positioning systems may be used to estimate the target location coordinates. This position information may provide sufficient precision for surveillance purposes or some targeting missions. However, the use of a laser range finder onboard the UAV provides actual slant range to targets and provides precise target location data, even under varying terrain conditions.

e. *Radar*

An obvious way to increase UAV sensor range is to use an active detection system such as radar. Active sensors also provide precise range information for instantaneous target location, which passive sensors do not. Moving target indicator (MTI) radar for UAVs allows detection of targets

moving faster than 4 meters per second within a 15 kilometer radius of the UAV. This system increases the rate of coverage over typical optical sensors by approximately a factor of 170 (Shyman, 1988, pp. 1-2). A radar system usually adds more weight to the UAV than do passive sensors, but MTI systems that weigh as little as 125 pounds are currently available. However, this represents relatively advanced technology which may not be available to all nations. Also, MTI radar equipment is probably too expensive to justify use on inexpensive UAV platforms that will suffer high attrition. The major drawback of active sensors is that they are easily detectable by opposing forces. Also, radar does not provide positive target identification, which is typically required by U.S. rules of engagement; opposing forces may not have such demanding target identification requirements.

4. Data Transfer

There are two primary types of non-lethal UAVs: those with real-time data link capability, and those without; both present a threat to ground forces. However, these threats are different. A UAV with real-time imagery capability endangers ground forces as soon as it closes to the effective range of its sensors and allows long range targeting of these forces. As the duration of UAV real-time imagery of a ground force increases, the effectiveness of an attack based on that information increases. Continuous surveillance of a target

allows for correction of fire and battle damage assessment, which greatly increase the probability that the target is destroyed.

A UAV designed to collect and record surveillance information during its flight with no data link capability cannot provide immediate targeting information on ground forces. These UAVs provide information only after recovery. However, the ground forces detected by a UAV are susceptible to follow-on attack if they are not mobile enough to clear the area of detection, or to counter-attack before the UAV information is processed. It is clearly desirable that U.S. ground forces be able to determine if they have been observed by a surveillance UAV. Changes in positions of ground units detected by UAV sensors may reveal U.S. strategy and allow anticipation of future actions; this is an important mission of endurance UAVs. Thus, the UAV information transfer configuration determines the susceptibility time window for ground forces detected by UAV sensors.

5. Attack

UAVs endanger ground troops in two ways: direct and indirect attack. A non-lethal UAV may provide real-time target location data or target designation for artillery, naval gunfire, and missile attack; or it may jam ground sensors and communications. A lethal UAV will fly directly at detected ground units for attack. The primary difference

between these two dangers is that the UAV targeting for other weapon systems can effectively guide weapons to, or jam, the ground unit from its maximum effective sensor or jammer range, while a lethal UAV must close to within the lethal radius of its weapon for successful attack. Lethal weapon radius is typically much shorter than sensor range. Although the lethal UAV may present a more tangible danger to ground troops, it must fly much closer to U.S. forces than a non-lethal UAV to inflict damage. A jamming UAV may be able to effectively jam from a distance of 6 kilometers; a reconnaissance UAV may provide accurate targeting information from 1.5 kilometers; a lethal UAV may have to achieve a direct hit to be effective (Smith, 1987, p.185). These differences allow various reaction times for ground forces.

Laser range finders allow a UAV to provide extremely precise targeting data for weapons. A laser target designator aboard the UAV potentially provides precision munitions guidance. This precision is required to minimize collateral damage to non-military elements near military targets and was successfully demonstrated by coalition forces in the Gulf War.

Virtual attrition is the reduction of a combat force's effectiveness due to the perception of significant threat from opposing forces if certain actions are taken. The force's effectiveness is lower than expected due to the anticipated hostile force action. For example, if air defenses are successfully shooting down low level bombers, the bombers may

elect to perform high altitude bombing runs which are not as accurate and do not cause as much damage even though no more aircraft are being shot down at low level. (Ball, 1992, p. 9)

Lethal UAVs contribute to overall combat effectiveness through direct attack of ground forces and virtual attrition of ground forces. Hostile ground forces may become less willing to radiate active sensors when they risk destruction by lethal anti-radiation UAVs. Virtual attrition effects will increase as enemy ground forces are successfully attacked by UAVs. This effect will increase the survivability of ground forces using UAVs (Karch, 1990, p. 50).

B. ANTI-UAV DEFENSE

1. Intelligence

An effective anti-UAV weapon system should be successful against many types of UAVs. However, accurate intelligence information will narrow the spectrum of UAV characteristics to be defended against in a specific region or conflict. For this reason, sensor and weapon modularity significantly improve the potential effectiveness of an anti-UAV weapon system. The anti-UAV system may be tailored to the anticipated threat to maximize effectiveness. Modularity also provides the capability of integrating multiple acquisition and attack modules to maximize sensor and weapon coverage. For example, if it is known that an opposing force possesses pre-programmed autonomous UAVs, an anti-UAV system relying

solely on detection of control link emissions will be inadequate.

Ideally, UAV launch and support facilities will be targeted and destroyed before UAVs are used against U.S. forces (Murphy, 1987, p. 69). However, short range UAVs may be dispersed throughout the battlefield, making complete destruction difficult. UAV ground support facilities are smaller and more difficult to locate than are manned aircraft facilities. However, UAV facilities may be less well defended and located closer to the enemy and therefore, are more likely to be attacked than conventional airports. The ground support element is likely the least redundant component of most UAV systems and therefore a priority target.

2. Point Versus Area Defense

A major issue in air defense is the transition between area and point defense. This distinction is determined by the mission and mobility of the unit defending against UAVs. Area defense is appropriate for high value regional assets such as Patriot missile sites, logistics depots, or command and control centers. Point defense is appropriate for local assets such as dispersed, highly mobile units.

Area defense against UAVs is made especially difficult by the inherent low-observable characteristics of UAVs. Long range detection of UAVs is accomplished only by high power radars. These systems are expensive, relatively immobile, and

quite possibly will require protection against UAV attack themselves while engaged in the air battle.

The difficulty of long range detection of UAVs implies that an effective anti-UAV weapon must be capable of moving with the ground maneuver forces it is to protect. In the case of defending armored units, the anti-UAV system must be able to move with the leading elements through difficult terrain or water, with sufficient armor to survive close combat (Ball, 1985, pp. 110-111).

3. Search and Surveillance Capabilities

Active search for UAVs seems desirable because radar systems have relatively large search volumes and long detection ranges. However, active radar systems are detectable by enemy forces, and are susceptible to anti-radiation attack. Long range radar search for UAVs is only appropriate for units that do not require covertness or high mobility.

a. Radar

Reliable detection of UAVs with radar cross sections as small as 0.001 m^2 is possible at ranges of 65 kilometers or greater using systems such as the AN/TPS-32 or AN/TPS-70 long range tactical air defense radars. These systems are transportable by truck, aircraft, or helicopter, but require substantial time and effort to reposition and are considered relatively fixed-position, long range assets.

(*Jane's Radar and Electronic Warfare Systems 1991-92*, 1991, pp. 74-75)

Air defense surveillance radars like the TPQ-36A system can detect some UAVs at ranges of 14 kilometers or greater. These radars are highly mobile and are transportable by light vehicles or aircraft. The TPQ-36A provides high three dimensional accuracy in severe clutter and electronic counter measure (ECM) environments. Use of a low sidelobe, electronically phase-scan, pencil beam antenna minimizes clutter effects for low level detection, hostile ECM effectiveness, and susceptibility to anti-radiation attack. (*Jane's Radar and Electronic Warfare Systems 1991-92*, 1991, p. 73)

Battlefield surveillance radars like the Portable Search and Target Acquisition Radar (PSTAR) system allow detection of UAVs at ranges of 4 kilometers or greater. These portable systems are designed for use by light infantry units. These systems have the ability to reduce ECM effectiveness and to provide excellent detection in high clutter. The PSTAR system is designed for deployment from the High Mobility Multi-Wheeled Vehicle (HMMWV), and can move in and out of positions in less than 10 minutes. The PSTAR system also is capable of near real-time interface with command and control networks or weapons platforms. (*Jane's Battlefield Surveillance Systems 1990-91*, 1990, p. 60)

Radar systems provide a wide spectrum of UAV detection capability and often determine all information required for weapon delivery. The primary disadvantage of radar systems is that they are detectable by the enemy and therefore, may not be suitable for clandestine operations.

b. Optical

Optical detection of UAVs is highly dependent on environmental factors. Increased detection range is attained by magnification which reduces the visual field-of-view, decreasing surveillance area and increasing search time. Use of visual sensors is also a very fatiguing and demanding human task. Essentially, visual sensors are inefficient search mechanisms. Given cuing by more efficient search sensors however, visual sensors may be effective for UAV surveillance and tracking. Detection ranges as great as 10 kilometers are possible depending on UAV aspect and environmental conditions. Visual sensors are passive and do not present any counter-detection problems. (Dynetics, 1991, pp. 6-1 - 6-20)

c. FLIR

Infrared detection of UAVs is highly dependent on environmental conditions and UAV temperature. This method also places high demand on human operators. Narrow field-of-view is required to achieve detection at ranges near 6 kilometers, making search area very small and search time long. Wide field-of-view FLIR detection probably only yields

ranges of 2-3 kilometers. FLIR is an inefficient search sensor and may only be adequate for surveillance once cued by other means. (Dynetics, 1991, pp. 4-1 - 4-18)

The use of multiple UAVs in a single mission must also be considered. A master UAV may be used to provide targeting information for other lethal UAVs. Multiple targets for a single optical or FLIR sensor may overload the operator and make anti-UAV defense very difficult. There should be some method of ensuring that a single sensor has the capability of tracking multiple targets or that sensors are assigned to specific targets such that no target is unaccounted for.

d. *Infrared Search and Track (IRST)*

IRST sensors operate much like scanning radar systems without the benefit of range capability. This concept essentially employs an infrared sensor linearly scanning a circle. Multiple scans or sensors allow full 360 degree coverage of 20 degrees of elevation. This reduces the human limitations of FLIR systems and sophisticated filtering techniques may provide reliable detection in clutter (*Jane's Battlefield Surveillance Systems 1990-91*, 1990, p. 89). These systems are in the developmental stage and may provide detection ranges of 3-5 kilometers. (Dynetics, 1991, pp. 5-1 - 5-9)

e. *Passive Radio Frequency Intercept*

UAV active emissions are exploitable for detection by ground forces. Real-time data links, radar altimeters, jamming equipment, and radar sensors may be detectable. This method provides bearing-only information but, resolution of less than 15 degrees can be achieved within one second, 5 degrees within 10-20 seconds. It has been demonstrated that some low band emitters such as data links are detectable at ranges of 14 kilometers or greater. Active jammers and radars may be detectable at much greater ranges. (Dynetics, 1991, pp. 8-1 - 8-5)

Radio frequency intercept allows long range passive detection of active UAVs. This method requires minimal equipment and provides accurate bearing information very rapidly; even short bursts of intermittent data link transmission are detectable. Radio frequency intercept often provides electronic characterization of the emitter allowing platform classification by comparison to a library of emitter characteristics. Radio frequency intercept provides an excellent method of cuing other sensors such as FLIR or optical devices. However, detection of UAV data link transmissions is not completely reliable and may be totally ineffective against UAVs with fiber optic data links.

4. Multi-sensor Information Fusion

The diversity of UAV configurations and capabilities dictates that an effective anti-UAV system be capable of exploiting multiple UAV detection media in any weather or electronic environment. An anti-UAV system must also be able to defeat UAVs cost effectively. It is difficult to justify the use of the Patriot missile to destroy a UAV with capabilities similar to the Pioneer system. In fact, inducing a Patriot missile battery to fire at a UAV may be considered a successful UAV mission. However, if a Patriot radar detects a UAV at long range and provides fire control data for attack with a less expensive weapon, that may be considered a cost effective anti-UAV operation.

Active UAVs are the most detectable; their radars, jammers, or data links are detectable by radio frequency intercept at long ranges. This suggests that a passive radio intercept capability be part of any anti-UAV system. This allows detection of some remotely-controlled real-time data link capable UAVs which are the predominant and most time critical threat to ground forces.

Electronically passive autonomous UAVs present a challenge to anti-UAV systems since the UAVs do not produce detectable radio frequency emissions. Optical or FLIR systems are currently available for passive detection of these UAVs and both methods are inefficient at wide area surveillance. Since these UAVs are passive only, passive mobile ground

forces are not usually at risk. However, active ground systems such as radar sites or command and control centers, as well as fixed location units such as logistics centers, are subject to attack by passive UAVs searching for active emitters or following pre-programmed routes to fixed locations. Long range radar systems are appropriate for fixed location high value units. Surveillance or battlefield radars are appropriate for active ground forces which are relatively mobile or require limited detection ranges.

Non-real-time data link reconnaissance UAVs do not present immediate danger to mobile ground units and autonomous lethal UAVs must close to short ranges to attack ground forces. These situations allow short range detection and attack of these types of UAVs. A system like the initially proposed U.S. Army Air Defense Anti-Tank System (ADATS) uses a combination of frequency-hopping search and acquisition radar, FLIR, TV, and laser range finder sensors with laser guided missiles and high-rate-of-fire guns to detect and destroy airborne targets within a 25 kilometers radius, while moving. UAVs may be detectable to distances of several kilometers with a system such as this. ADATS also includes the capability to operate six units in a master-slave function in which only one unit needs active radar thereby minimizing detectability while maximizing firepower (Walters, 1990, pp. 82-88). The Hughes Electro-Optical Tracking System (EOTS) combines thermal imaging, TV, and high-repetition rate laser

range finder equipment to provide a detection system which is completely passive except for the laser, which is difficult to detect (*Aviation Week and Space Technology*, 1992, p.6). A system such as this may allow U.S. forces to detect UAVs, as well as other aircraft, without significant risk of counter-detection.

Thus, an effective anti-UAV system must include both passive and active sensors and be capable of transfer and receipt of data to and from other sensors and weapons platforms. The system must include highly mobile elements capable of protecting other mobile ground units from UAVs. Modular sensor and weapon capability will facilitate tailoring the system to the predominant threat.

IV. ANTI-UAV HYPERVELOCITY ROCKET WEAPONS

A. BACKGROUND

Hypervelocity rockets are similar to conventional rockets, but they travel at a higher speed. The Persuader 2.75 inch hypervelocity rocket travels approximately twice as fast as the conventional Hydra-70 2.75 inch rocket. High speed increases effectiveness in two ways. First, a less sophisticated fire control system is required since the time between launch and impact is less than half the time of existing rockets, allowing essentially a point and shoot capability. The fire control system must determine elevation and lead angles. The shorter time of flight reduces the probability that the target will successfully evade the projectile by maneuvering. Secondly, hypervelocity projectiles cause more damage than do equal-sized conventional projectiles because of their higher penetrator kinetic energy resulting from greater velocities. Penetrator kinetic energy is approximately four times that of conventional rockets. The result is a higher probability of kill given a single penetrator hit. Hypervelocity rockets also provide significantly longer maximum engagement ranges. (United Applied Technologies, 1991)

A hypervelocity rocket air defense weapon has been proposed for both ground forces and aircraft. Such a system may provide an effective anti-UAV capability. The weapon in this system is a hypervelocity rocket which is launched at the target, then detonates and disperses a large number of tungsten flechette penetrators some distance from the target (Figure 3).

The base design incorporates a rocket that detonates and disperses or sprays flechette penetrators passively at booster burnout. An optional electronic timer facilitates controlling the distance that the rocket travels before dispersing penetrators based on the target's range from the rocket. The axial distance from the target at which the rocket detonates and disperses its penetrators, called *detonation distance* and denoted by z, determines the radius of the penetrator spray pattern when it reaches the target (Figure 4). It may be feasible to incorporate a target detecting device in the rocket to precisely control detonation distance. Detonation distance may be optimally selected to maximize the probability that the rocket kills the UAV. If detonation distance is chosen too small, it becomes more likely that the penetrator spray is not dispersed enough to cover the target. If the detonation distance is chosen too large, the penetrator spray may be so sparse that no penetrators impact the target vulnerable area even though the spray covers the target.

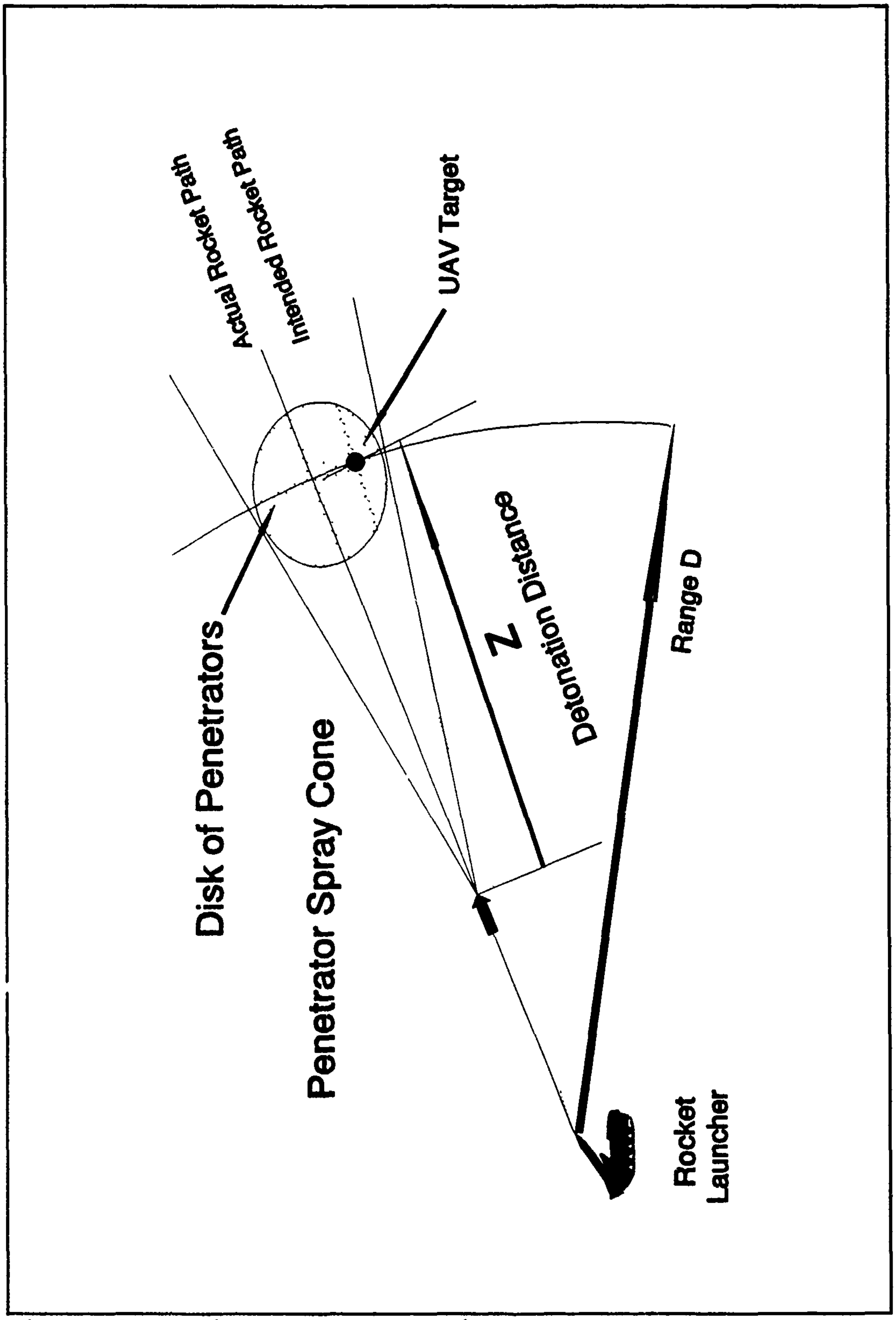

Figure 3 Anti-UAV Hypervelocity Rocket Weapon Concept

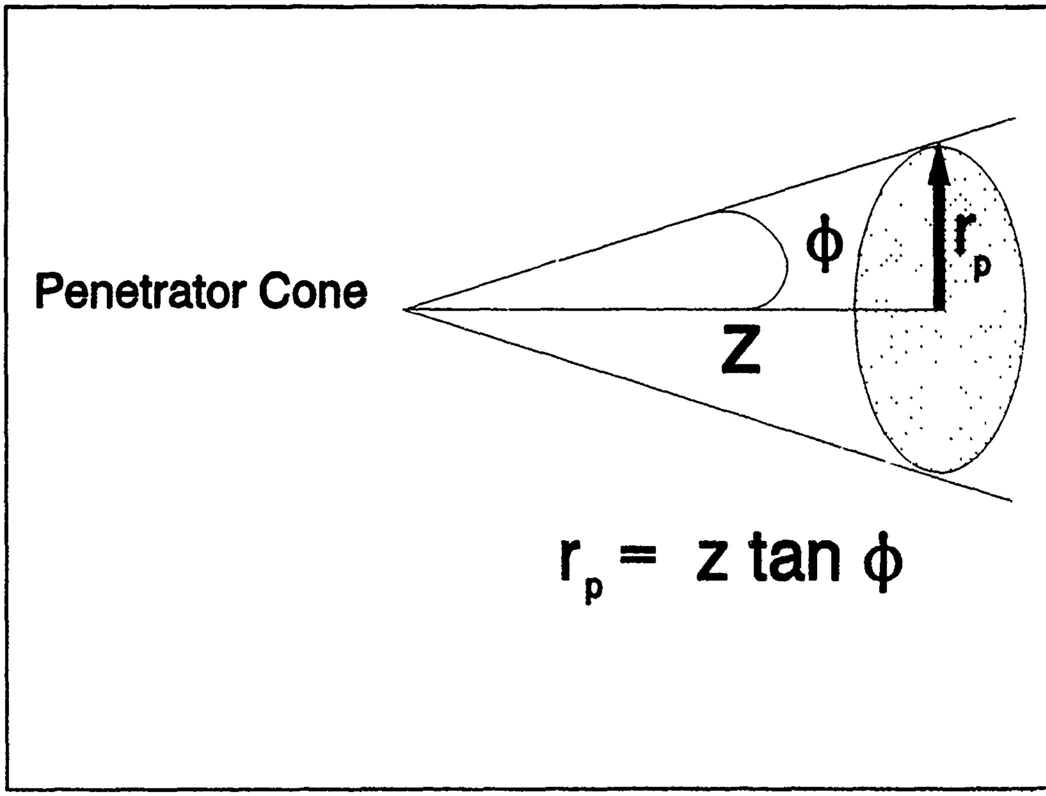

Figure 4 Penetrator Spray Cone Geometry

B. WEAPON LETHALITY

A lethal air defense weapon system is one that can encounter, engage, and kill aircraft. *Lethality* is the probability that the weapon system can kill the aircraft. Air defense lethality is the complement of aircraft survivability. Weapon lethality is a function of target susceptibility and vulnerability. (Ball, 1992, pp. 5-8)

Susceptibility is the aircraft's inability to avoid being hit (Ball, 1985, p. 223). The following is a list of some factors which influence susceptibility:

- environment
- threat characteristics and deployment
- tactics
- aircraft signatures
- aircraft countermeasures
- aircraft performance.

Vulnerability is the target's inability to withstand hits from a weapon (Ball, 1985, p. 135). Some factors which influence target vulnerability are:

- critical component redundancy
- critical component location
- critical component shielding
- critical component separation
- critical component elimination
- active and passive damage suppression.

1. UAV Vulnerability

Vulnerability is measured as the probability that the UAV is killed given a hit by the weapon. Vulnerability reduction is usually not incorporated extensively in UAV design because of cost constraints. The UAV is generally thought to be expendable and, therefore, survivability enhancement measures are often much less extensive than those for manned aircraft. UAVs typically have little redundancy in their design and critical components are not separated due to

space, weight, and center of gravity constraints, making them very vulnerable to attack. It is considered to be likely that hypervelocity rocket penetrators are large enough and travel fast enough that a single penetrator impacting the UAV vulnerable area will destroy the UAV or its sensor (United Applied Technologies, 1991); that is UAVs will be very vulnerable to hypervelocity rocket penetrators with a $P\{kill \mid hit\} \approx 1$. Thus in this thesis, given that the UAV can be detected and tracked, the weapon lethality is assumed to be determined by the probability that at least one flechette penetrator will hit the UAV vulnerable area. This analysis may be easily modified for study of weapons which must provide multiple penetrator hits to kill the target.

2. UAV Susceptibility

UAV susceptibility is measured as the probability of hit, which includes the probability of acquisition, detection, identification, tracking, launch, guidance, and detonation. Detection, acquisition, identification, and tracking have been addressed in classified UAV survivability studies (see bibliography), and hypervelocity rockets do not receive inflight guidance. The present analysis assumes that the rocket is successfully launched at a tracked target, but with some error due to tracking error and round-to-round dispersion. Thus, the probability of hit or damage is assumed

to be determined by the target characteristics, penetrator spray, and weapon delivery error.

The proposed hypervelocity rocket weapon system has demonstrated high reliability. More than 600 rocket motors were tested with no failures (United Applied Technologies, 1991). Thus, the issue to be examined in this thesis is the air defense endgame or the determination of the probability that at least one flechette penetrator will hit the target vulnerable area given a successful rocket launch.

C. ENDGAME

1. Weapon Delivery Error

The fire control solution for a target UAV will have inherent error and each rocket will detonate at a point some distance from its intended aim point due to round-to-round dispersion. Thus, the rocket will be delivered in the proximity of the target with some error. These errors include the effects of tracking error, wind effects on the projectile, and unpredicted target maneuvering. It is reasonable to assume that the rocket will reach the target's range with error components in azimuth and elevation, in the X and Y directions respectively (Figure 5). These error components are most often quantified as angular errors. It is assumed here that elevation and azimuth errors, denoted by A and E, are independently and identically normally distributed with mean zero and variances $\sigma^2_E = \sigma^2_A = \sigma^2$. Thus, errors E and A

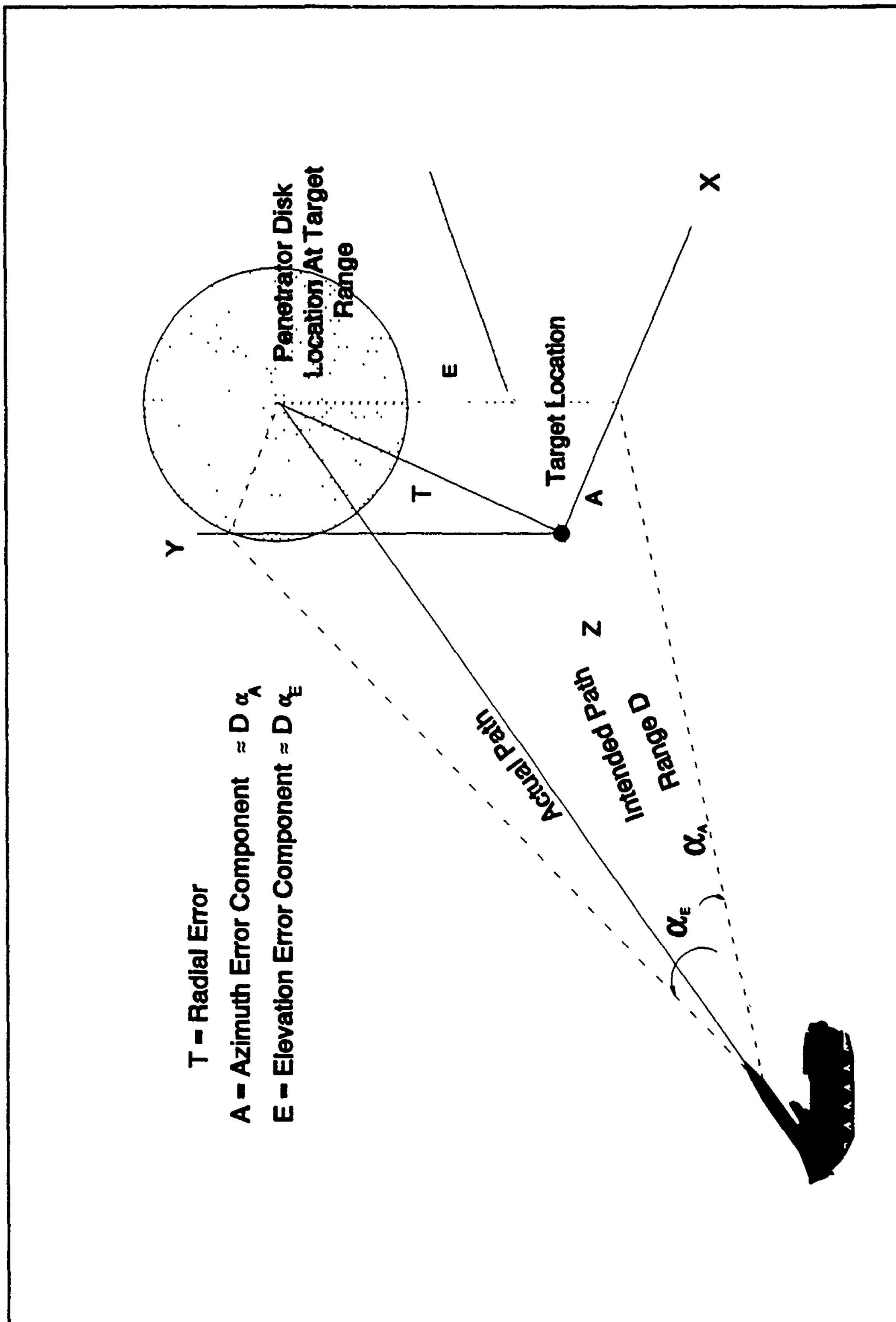

Figure 5 Weapon Delivery Error Diagram

are circularly normal. These errors may be combined to yield a radial miss distance T, where $T^2 = A^2+E^2$ is the sum of two independent, identically distributed, squared normal random variables, thus T^2/σ^2 is a Chi-Square random variable with 2 degrees of freedom.

A model for weapon delivery error in spherical coordinates is as follows. When considered in spherical coordinates, the fire control azimuth and elevation error components are angular errors from the ideal aim direction, denoted by α_A and α_E, (Figure 5). It is assumed that the weapon delivery is unbiased; mean angular error components are zero. The radial miss distance at the target range is determined by the target range and angular error components; $A = D\tan\alpha_A$ and $E = D\tan\alpha_E$. The radial miss distance at the target's range is a linear function of the engagement range, D, and the tangent of angular error (Figure 6). Typical weapon system angular errors are on the order of a few milliradians, as estimated by the U.S. Army Missile Command Advanced Systems Concepts Office. The tangent of these angles is very closely approximated by the angles (thus, $A \approx D\alpha_A$ and $E \approx D\alpha_E$). Angular error is an input parameter in the models developed in this thesis; the models are applicable for angular errors that are of magnitude such that the angle provides a close approximation of the tangent of the angle. Thus, the miss distance component variances depend on the

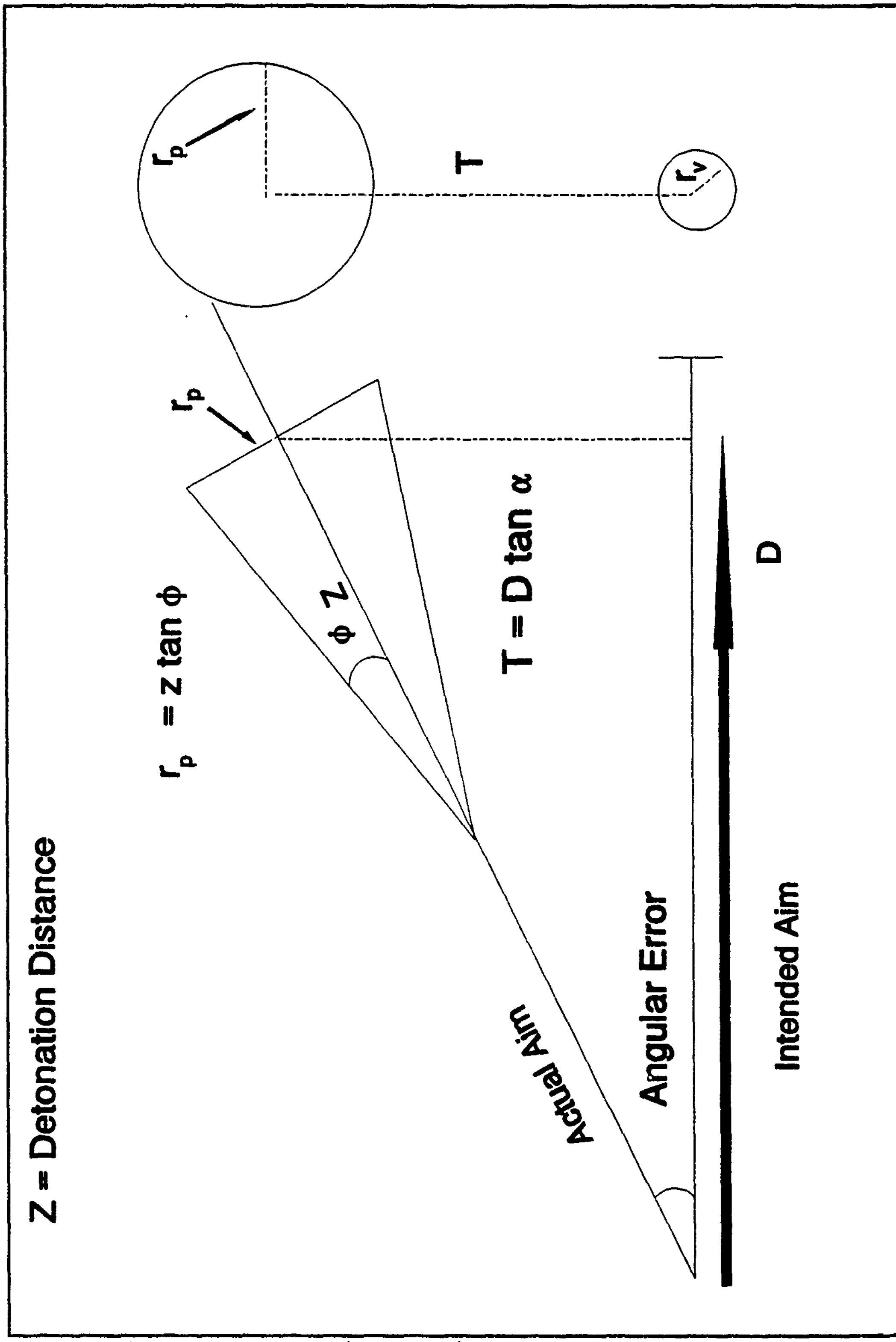

Figure 6 Polar Coordinate View of Endgame Geometry

distance D that the rocket travels to the target and the azimuth and elevation angular variances. Their approximations are: $Var(A) \approx D^2 Var(\alpha_A)$ and $Var(E) \approx D^2 Var(\alpha_E)$. It is assumed that the azimuth and elevation error components may be modeled as independent and identically distributed normal random variables therefore, $Var(A) = Var(E) = D^2 \sigma_\alpha^2$. Thus, $T^2 \div (D^2 \sigma_\alpha^2)$ is distributed as a Chi-square random variable with two degrees of freedom which is equivalent to an exponential random variable with rate parameter $\lambda = \frac{1}{2}$.

2. Reference System

The point of interest in this scenario is the instant when the penetrators reach the range of the target, where they either hit or miss the target vulnerable area. This is the terminal phase of the lethal air defense endgame. The center of the target vulnerable area is chosen as the origin of a spherical coordinate reference system (Figure 7). Detonation distance, z, is measured from the target center to the rocket position along the positive Z axis. The plane determined by z=0, at the target's position, determines a polar coordinate endgame reference system. It is assumed that the detonation distance can be controlled. Because of the radial error mentioned earlier, the center of the penetrator spray zone will be offset from the origin by random radial distance T. The amount of the penetrator spray which covers the target

depends only on the radial separation and is independent of angular offset if both areas are assumed to be circular.

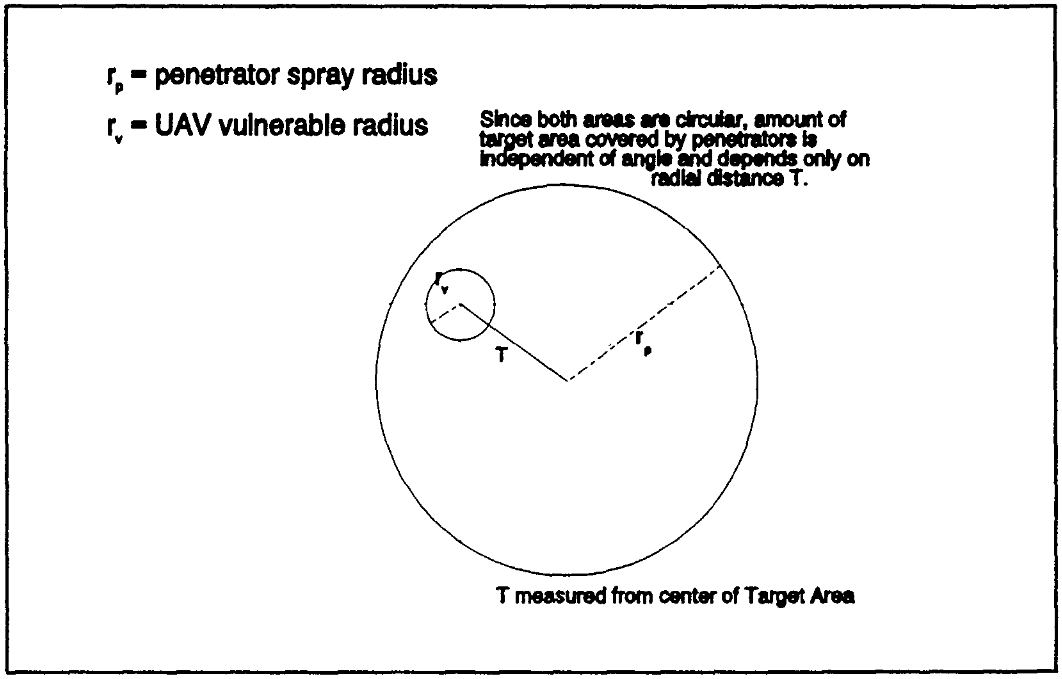

Figure 7 Polar Coordinate Reference System

3. UAV Vulnerable Area

The UAV critical components are assumed to occupy an approximately spherical volume at the center of the UAV. Therefore, the UAV vulnerable area is circular when viewed from any aspect. Since UAVs have small vulnerable areas relative to the size of the flechette penetrator spray, it is assumed that the projectile penetrator spray disk either completely covers or completely misses the UAV vulnerable area (Figure 8). This assumption simplifies probability of impact

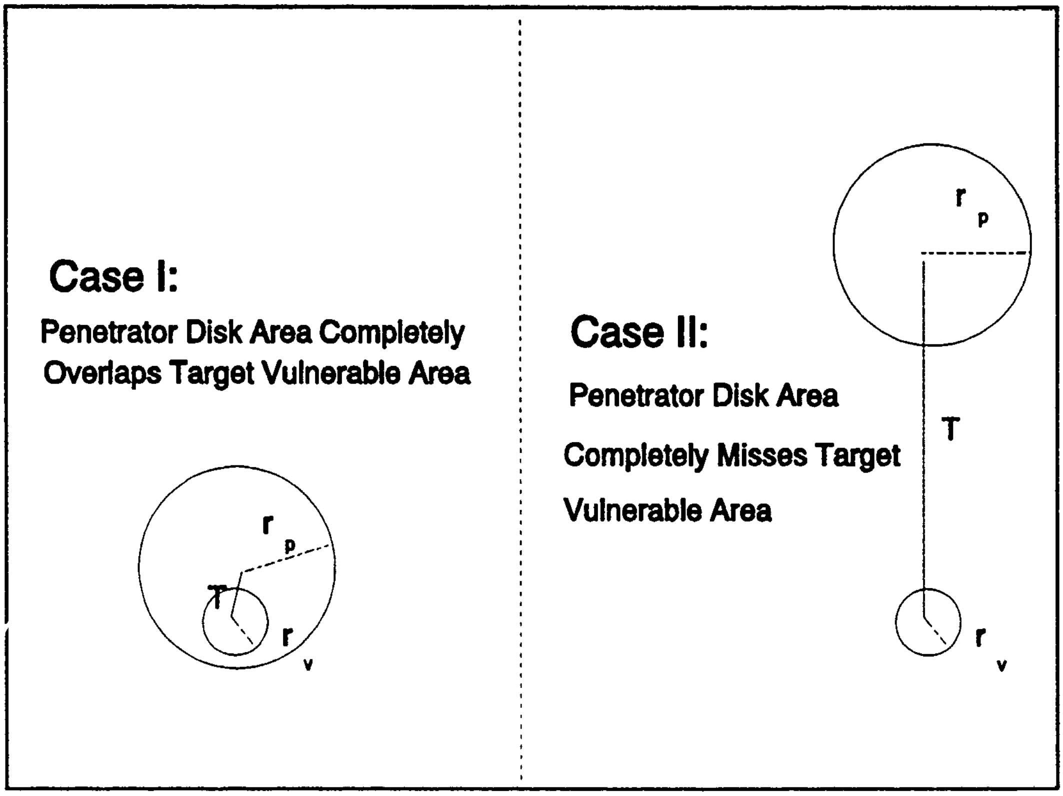

Figure 8 Endgame Analysis: Two Cases Considered

analysis by excluding the possibility that the projectile disk partially overlaps the target vulnerable area. Thus, two exhaustive and mutually exclusive cases are parameterized by: P_I = probability that penetrator spray completely covers the target vulnerable area and P_{II} = probability that projectile area completely misses the target vulnerable area. A more refined analysis is possible, but appears to be unnecessary. Probability bounds can be constructed, but are not studied in this thesis.

4. Cookie-Cutter Model: Penetrator Probability of Hit

It is next assumed that the penetrators are uniformly distributed across the penetrator spray disk when it reaches

the range of the target. If a cookie-cutter damage function is assumed, a penetrator which hits the target vulnerable area causes damage with probability one, and a penetrator which misses the target vulnerable area causes no damage. The cookie-cutter damage function is given by (4.1) (Eckler and Burr, 1972, p. 43), where (x_p, y_p) represents the penetrator's coordinates, (x_t, y_t) represents the center of the target vulnerable area, and r_v represents the target's vulnerable radius. All coordinate measurements are made from the origin on the actual path of the rocket at the target's range.

$$d[(x_p,y_p),(x_t,y_t)] \begin{array}{l} = 1 \text{ if } \sqrt{(x_t-x_p)^2 + (y_t-y_p)^2} \le r_v \\ = 0, \text{ otherwise} \end{array} \qquad (4.1)$$

If the penetrator spray disk completely misses the target vulnerable area, no penetrators impact the target vulnerable area. If the projectile disk completely covers the vulnerable area, each penetrator has an equally likely, independent probability of impacting the target vulnerable area. This probability is determined by the ratio of target vulnerable area to projectile spray disk area. This ratio yields probability $\rho = \pi r_v^2 \div \pi r_p^2 = r_v^2 \div r_p^2$; it is assumed here that r_p is greater than r_v, which is totally realistic for most of the projectile trajectory. Hence, given that the projectile disk completely covers the vulnerable area, the number of penetrators which impact the vulnerable area is binomially distributed with probability ρ and number of trials n, the number of penetrators. The number of penetrators which

miss the target is binomially distributed with probability $1-\rho$ and number of trials or penetrators n. Thus, if each projectile contains n penetrators, the probability that no penetrators impact the target vulnerable area given complete overlap exists, denoted by P_0, is determined by (4.2).

$$P_0 = \left(1 - \frac{r_v^2}{r_p^2} \right)^n \tag{4.2}$$

5. Probability That Penetrator Spray Covers Target

As stated above, only the cases of complete overlap and complete miss are considered. Edge effects, that should be considered when partial overlap exists, are excluded based on the assumption that UAV vulnerable areas are small relative to penetrator spray pattern size and error offset of pattern center. Calculation of the probability that the penetrator disk completely overlaps the vulnerable area, P_I, is given by the probability that the radial miss distance (T) is less than or equal to the penetrator spray disk radius (r_p), as in (4.3a). The probability that the projectile spray disk misses the target vulnerable area is the complement, $P_{II} = 1-P_I$ as in (4.3b).

$$P_I = P\,(T \le r_p) = 1 - e^{-\frac{1}{2}\frac{r_p^2}{D^2\sigma_e^2}} \tag{4.3a}$$

$$P_{II} = P\ (T > r_p) = e^{-\frac{1}{2}\frac{r_p^2}{D^2\sigma_e^2}} \tag{4.3b}$$

6. Probability of No Penetrator Hits

There are two ways which the UAV vulnerable area may receive no penetrator impacts. First, the penetrator spray area may completely miss the target vulnerable area. Secondly, the areas may overlap but all penetrators miss the vulnerable area. Thus, the probability of no penetrator hits given detonation distance z equals the probability of no overlap plus the probability of complete overlap times the probability of n misses given overlap. Combining the probability equations for both cases, $P_{no\ hits\ |\ z} = P_{II} + P_I\ P_0$, yields (4.4).

$$P_{no\ hits\ |\ z} = e^{-\frac{1}{2}\frac{r_p^2}{D^2\sigma_e^2}} + (1 - e^{-\frac{1}{2}\frac{r_p^2}{D^2\sigma_e^2}})\ (1 - \frac{r_v^2}{r_p^2})_+^n \tag{4.4}$$

The geometry of Figure 4 shows that the penetrator spray radius $r_p = z\tan\phi$. Note that the + subscript means that the term is set to zero if the argument is negative. Thus, substitution for r_p yields (4.5).

$$P_{no\ hits\ |\ z} = e^{-\frac{1}{2}\frac{z^2\tan^2\phi}{D^2\sigma_e^2}} + (1 - e^{-\frac{1}{2}\frac{z^2\tan^2\phi}{D^2\sigma_e^2}})(1 - \frac{r_v^2}{z^2\tan^2\phi})_+^n \tag{4.5}$$

It is assumed that the penetrator spray zone is conical with fixed half angle (ϕ). The probability that a

penetrator hits the target depends on $\tan\phi$. Various values of ϕ were examined and the maximum probability of at least one hit was obtained at an angle of approximately 15 degrees. Rocket design constraints may dictate this angle. Letting constant $c_1 = \tan^2\phi$ yields (4.6). It is assumed that

$$P_{no\ hits\ |\ z} = e^{-\frac{1}{2}\frac{c_1 z^2}{D^2\sigma_\alpha^2}} + (1 - e^{-\frac{1}{2}\frac{c_1 z^2}{D^2\sigma_\alpha^2}})\ (1 - \frac{r_v^2}{c_1\ z^2})_+^{\ n} \qquad (4.6)$$

detonation distance z depends on engagement range D; the probability of at least one hit is determined for a specific scenario in which engagement range is constant. Therefore, let $c_2 = c_1 \div D^2\sigma_\alpha^2$. Thus, $c_2 = \tan^2\phi \div (D^2\sigma^2_\alpha)$ and substitution yields (4.7). The probability of at least one

$$P_{no\ hits\ |\ z} = e^{-\frac{1}{2}c_2\ z^2} + (1 - e^{-\frac{1}{2}c_2\ z^2})\ (1 - \frac{r_v^2}{c_1\ z^2})_+^{\ n} \qquad (4.7)$$

hit is equal to one minus the probability of no hits. Thus, the probability of at least one hit is given by (4.8). This

$$p(z) = P_{\geq 1\ hit|z} = 1 - e^{-\frac{1}{2}c_2 z^2} + (1 - e^{-\frac{1}{2}c_2 z^2})\ (1 - \frac{r_v^2}{c_1\ z^2})_+^{\ n} \quad (4.8)$$

may be maximized with respect to detonation distance (z) and will be a function of engagement range (D), a characteristic of the scenario, and spray cone half-angle (ϕ), a characteristic of the weapon design. In order to do this, one approach is to set the derivative with respect to z for this probability equal to zero to obtain an equation for optimal detonation distance. The solution must be checked to verify

a maximum and not a minimum. However, in the present problem this procedure does not yield a closed-form solution for optimal detonation distance. As an alternative, the probability of at least one hit as a function of detonation distance (z) may be calculated using a computer program such as that in Appendix A. The optimal detonation distance for a specific scenario may also be determined by a non-linear optimization program such as that in Appendix B. A graph of the probability of at least one hit is also important; it shows that the function p(z) is somewhat flat near the maximum, particularly at longer ranges. The graph reveals that the probability of kill curve, as a function of detonation distance, falls off sharply from its maximum value for short range engagements.

7. Optimal Detonation Distance Dependence on Range

Since the variance of radial error components ($D^2\sigma_\alpha^2$) is proportional to target range D, the optimal detonation distance (z) is dependent on the range from the weapon launch platform to the target. The probability at least one penetrator impacts the UAV vulnerable area may be computed for a specific size UAV at a given range and plotted as a function of detonation distance. Plots for different ranges reveal how the optimal detonation distance varies with range for a given size of UAV.

Figure 9 shows these plots for a UAV with a 5 square meter vulnerable area engaged by a hypervelocity rocket weapon with these characteristics: n=100 penetrators, $\sigma_\alpha = 5$ milliradians for angular error deviations, and ϕ=15 degree dispersion cone half-angle. These data are completely hypothetical and do not accurately reflect actual UAV vulnerable areas or hypervelocity rocket performance characteristics. This prevents disclosure of classified and proprietary data. Optimal detonation distances may be tabulated for various ranges and target vulnerable areas. This data may be stored in a fire control computer for rapid determination of fuzing time delay which provides the optimal detonation distance for a given engagement.

These tabular data may be used to set rocket fuse delay to maximize the effectiveness of anti-UAV hypervelocity rockets. The fire control computer will estimate the target's range. However, the UAV vulnerable area will not be as readily available and is aspect dependent. The operator may be able to input a UAV vulnerable area estimate based on intelligence or visual detection. In the absence of any intelligence data or visual detection, an expected UAV vulnerable area may be used. The UAV aspect presented to the weapon may be estimated by the relative closure of the UAV to the tracking sensor. It may be possible to provide the fire control system with a library of UAV physical and electronic

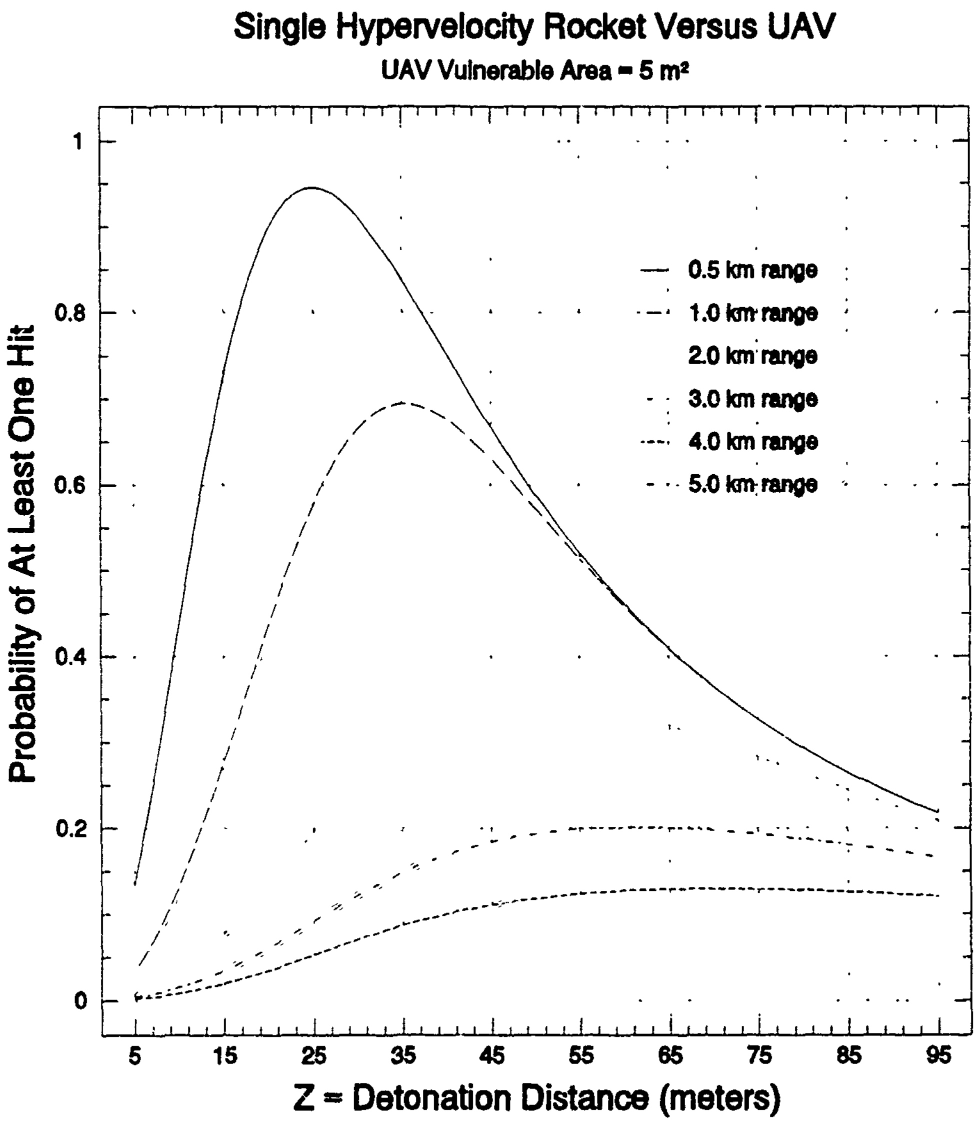

Figure 9 Cookie-Cutter Probability of Kill as a Function of Detonation Distance

characteristics which would allow automated target recognition equipment to provide the necessary parameters to retrieve aspect dependent UAV vulnerable area estimates from memory. This will provide an automated means of accurately estimating the UAV vulnerable area required to set detonation distance for optimal attack of UAVs. Figure 10 shows how optimal detonation distance and maximum probability of kill vary with target vulnerable area for a target range of 1 kilometer. It is shown that small targets are best attacked with relatively short detonation distances. This probably results because the shorter detonation distances provide a more dense penetrator spray required to ensure that a small target is killed.

D. JUSTIFICATION OF ASSUMPTIONS

For the hypothetical engagement discussed previously, the ratio of penetrator spray radius to UAV vulnerable area radius varies from about 6.7 at an engagement range (D) of 0.5 kilometers to 21.2 at an engagement range of 5 kilometers. The radial miss deviation varies from 2.5 meters at an engagement range of 0.5 kilometers to 25 meters at an engagement range of 5 kilometers as compared to a vulnerable radius of 1.26 meters. These data support the assumption that UAV vulnerable radius is much smaller than the penetrator disk radius and radial miss distance, justifying exclusion of partial coverage of the target vulnerable area from consideration.

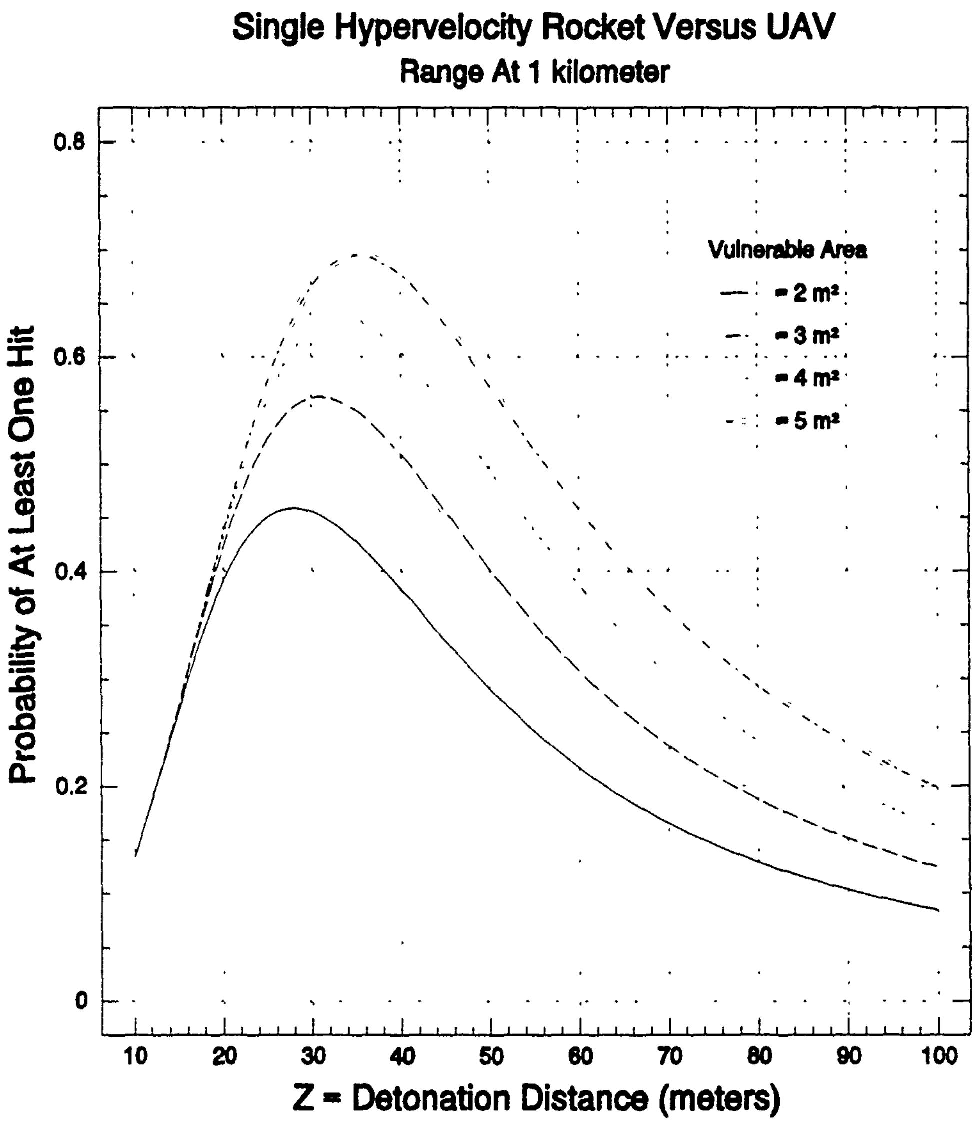

Figure 10 Probability of Kill and Optimal Detonation Distance as a Function of Vulnerable Area

E. SENSITIVITY ANALYSIS

The probability that a UAV is killed by a hypervelocity rocket depends on the UAV vulnerable area presented to the penetrator. Examination of probability of kill as a function of the difference between estimated and actual target vulnerable area, when the detonation distance is set to maximize probability of kill for the estimated vulnerable area, reveals the sensitivity of the probability of kill to errors in the UAV vulnerable area estimates.

Figure 11 shows the percent degradation of probability of kill from the maximum value for engagement ranges of 0.5 and 3 kilometers. This plot reveals that the model is relatively insensitive to vulnerable area estimate errors at long range; the probability of kill is degraded less than 3.5 percent for the 3 kilometer engagement. However, the probability of kill may be decreased by as much as 8 percent at an engagement range of 0.5 kilometer. Accurate vulnerable area estimates for close-in UAV engagements may provide significant improvements in weapon lethality. It appears that underestimating the target vulnerable area reduces lethality more than overestimating.

These data are hypothetical; however, the same type of analysis may be performed for real data. An analysis such as this would reveal whether it is more detrimental to err on the high or low side; asymmetry would suggest hedging by use of a

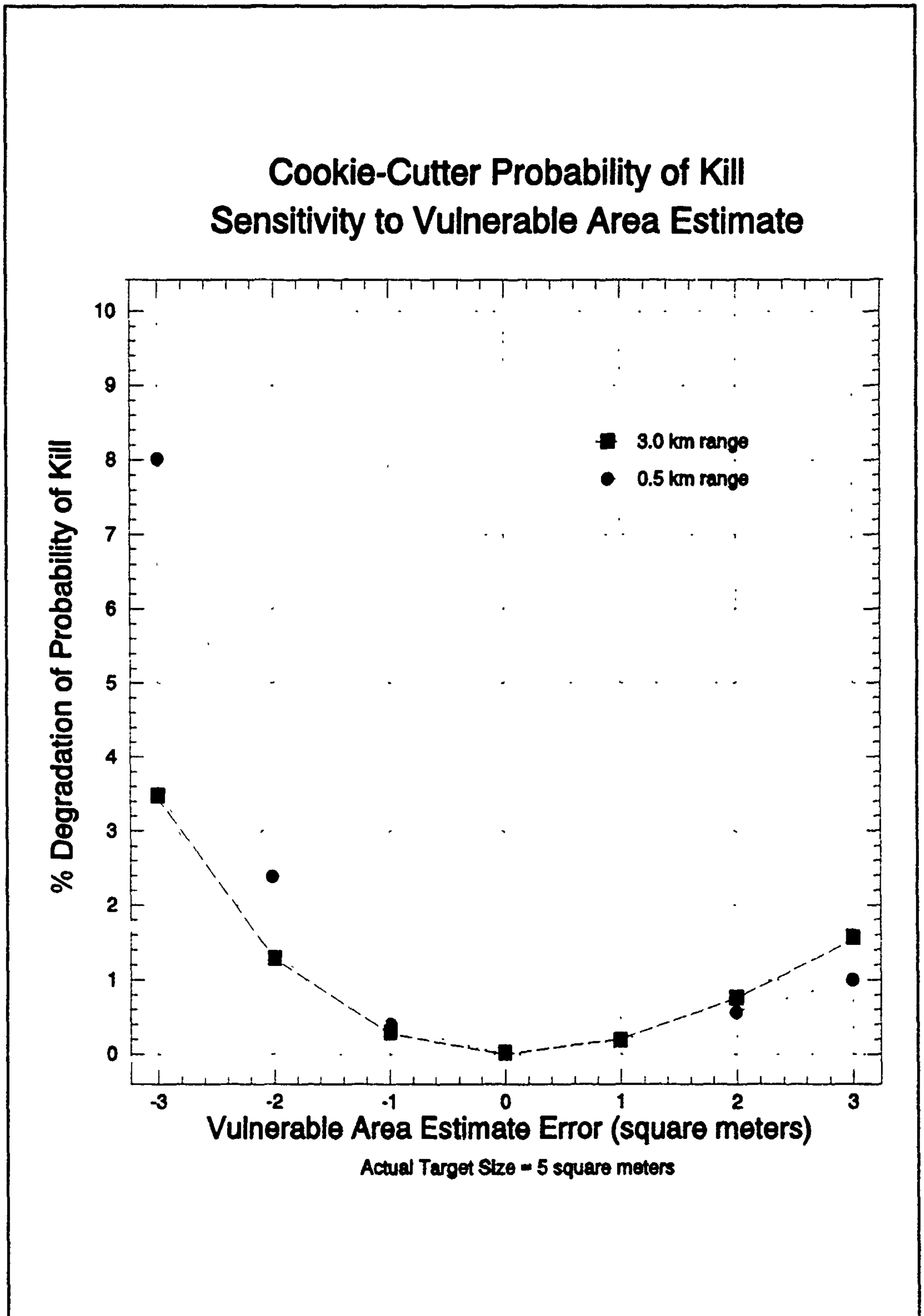

Figure 11 Cookie-Cutter Model Sensitivity to Target Vulnerable Area Estimate Error

biased estimate. More extensive sensitivity analysis may also reveal, as in the case of the 3 kilometer engagement for these data, that the vulnerable area estimate is not extremely critical for weapon lethality in certain scenarios. Since the weapon lethality is relatively sensitive to vulnerable area errors for short range engagements, UAV vulnerability data are critical to the optimal design of an effective hypervelocity rocket weapon for close-in defense. This may indicate that a UAV vulnerable area estimate biased for overestimation provides a more robust probability of killing the UAV. This indicates that the fire control computer should determine detonation distance based on top, bottom, or side aspect vulnerable areas rather than front or back aspect areas which are much smaller and could provide an underestimation of the UAV vulnerable area for the aspect presented to the rocket.

V. DIFFUSE GAUSSIAN MODEL

A. BACKGROUND

Cookie-cutter damage models, such as that of the previous chapter, are based on the assumption that damage occurs only if the damage mechanism penetrates within a rigidly specified radial distance from the center of the target vulnerable area.

The general requirement for a damage function is that it be non-increasing from one to zero along any radius outward from the origin (Eckler and Burr, 1972, p. 43). The diffuse Gaussian damage function, also known as the Von Neumann or Carleton damage function, is a common alternative to the cookie-cutter function. The diffuse Gaussian damage function is given by (5.1). Here r represents the radial distance from

$$d(r) = e^{-\frac{r^2}{2b^2}} \tag{5.1}$$

the center of the target to the penetrator position at the range of the target. Note that an asymmetric damage function may be used in the following analysis with no difficulty.

Unlike the cookie-cutter function, the diffuse Gaussian function provides a positive probability of damage for a penetrator impact at any finite distance away from the center of the target; however, the damage assessed by (5.1) falls off nearly to zero very quickly with radial distance from the target center. The diffuse Gaussian function is based on the

assumption that targets are more likely to be damaged if hit near some vital point and less likely to be damaged if hit further from away from this point. This is a more realistic model since most targets do not usually have all vulnerable components concentrated in a spherical volume. Figure 12 shows a comparison of the cookie-cutter and diffuse Gaussian damage functions.

The parameter b is, by convention, determined such that the total damage possible is equated to the presented area of the target. With r_{ap} equal to the radius of the presented target area which is assumed to be circular, $b = r_{ap} \div \sqrt{2}$ follows from (5.2) (Ball, 1985, p. 268).

$$\int_0^{2\pi} \int_0^{\infty} e^{-\frac{r^2}{b^2}} r \, dr \, d\theta = A_p = \pi r_{ap}^2 = 2\pi b^2 \qquad (5.2)$$

The cookie-cutter model of the previous chapter assumes a circular vulnerable area. Selection of parameter b such that the damage function integrates to the vulnerable area, vice presented area, yields $b = r_v \div \sqrt{2}$. This allows direct comparison of the two models.

For targets such as manned aircraft, the critical components are likely to be separated by relatively large distances. The use of a parameter b based on presented area will be more appropriate for analysis of this type of endgame. However, since UAVs are much smaller than traditional targets, models based on vulnerable area provide reasonable

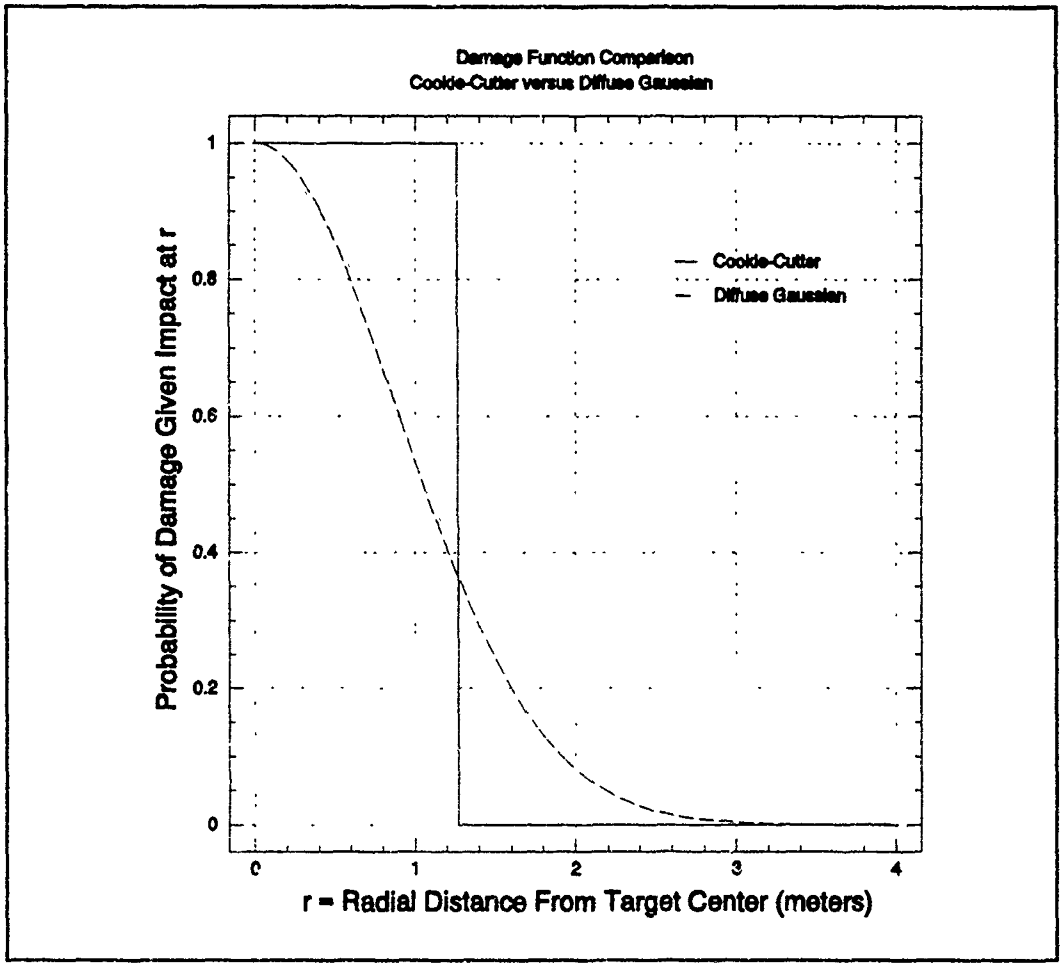

Figure 12 Damage Function Comparison

approximations of the endgame. The assumption that $b = r_v \div \sqrt{2}$ will be used in the remainder of this chapter.

B. ASSUMPTIONS

1. Target

The diffuse Gaussian damage function does not assume that the target has a spherical critical volume, which implies a circular vulnerable area. The diffuse Gaussian function allows damage to the target even for impacts outside a cookie-

cutter vulnerable radius. This is probably a more realistic representation of the probability of damage to an aircraft. Critical systems such as fuel tanks, sensors, engines, and propellers or rotors are usually located in various sections of the aircraft. Since UAVs are typically much smaller than manned aircraft, center of gravity or weight and balance constraints are much more stringent. Most UAV critical components are probably located near the aircraft's center of gravity but some, such as a propeller, are likely to be separated from this point. Thus, the diffuse Gaussian damage function may allow more realistic modelling of the hypervelocity rocket versus UAV endgame than does the cookie-cutter damage function.

2. Penetrator Spray

The cookie-cutter model assumes that the hypervelocity rocket flechette penetrator spray is conical in shape with deterministic half-angle. It was also assumed that the penetrators were uniformly distributed across the disk defined by the leading edge of the cone. However, it may be that in a real weapon the penetrators will be highly concentrated near the center of the spray cone and sparsely concentrated at the fringes of the spray cone. The spread of the penetrators, the bivariate deviation, should be a function of the detonation distance and the spray cone half-angle. Thus, $\sigma_p = f(z,\phi)$. It is therefore assumed that penetrators are spread across the

spray cone according to a bivariate normal density around the axis of the cone along the actual rocket path. The position of a penetrator (x_p, y_p), relative to the rocket spray pattern center at (0,0), is assumed to be distributed according to the bivariate normal density given by (5.3).

$$p\,(x_p,\,y_p) \;=\; \frac{e^{-\frac{1}{2}\frac{x_p^2}{\sigma_p^2}}}{\sqrt{2\pi}\,\sigma_p}\;\frac{e^{-\frac{1}{2}\frac{y_p^2}{\sigma_p^2}}}{\sqrt{2\pi}\,\sigma_p} \qquad (5.3)$$

3. Weapon Delivery Error

It is assumed that the rocket will be delivered to a position separated from the actual target location by a radial and angular error. As in the cookie-cutter model, this error is comprised of normal components in elevation and azimuth and is characterized by angular errors. As in the previous chapter, the squared radial error or miss distance divided by error component variance is modeled as a Chi-square random variable. The miss distance component standard deviations are approximated by $D\sigma_\alpha$.

C. PROBABILITY OF DAMAGE CALCULATION

The diffuse Gaussian damage function, based on the radial distance between the flechette penetrator and the center of the UAV vulnerable area, is given by (5.4).

$$P_{damage\,|\,(x_p,\,y_p),\,(x_t,y_t)} = e^{-\frac{1}{2}\frac{((x_p-x_t)^2+(y_p-y_t)^2)}{b^2}} \qquad (5.4)$$

Integration over the range of penetrator locations (x_p, y_p), as in (5.5), yields the probability of damage given the target center location coordinates (x_t, y_t).

$$P[\,damage \mid (x_t,\, y_t)\,] = \int_{-\infty}^{+\infty} e^{-\frac{1}{2}\frac{(x_t - x_p)^2}{b^2}} \frac{e^{-\frac{1}{2}\frac{x_p^2}{\sigma_p^2}}}{\sqrt{2\pi}\ \sigma_p}\, dx_p \int_{-\infty}^{+\infty} e^{-\frac{1}{2}\frac{(y_t - y_p)^2}{b^2}} \frac{e^{-\frac{1}{2}\frac{y_p^2}{\sigma_p^2}}}{\sqrt{2\pi}\ \sigma_p}\, dy_p \qquad (5.5)$$

If each integral is multiplied and divided by $(2\pi)^{1/2}$, then each integral amounts to a convolution of two normal random variables. The first integral has normal random variables x_p and $(x_t - x_p)$ with variances σ_p^2 and b^2 respectively; the second integral has the same normal random variables for the y components of the endgame geometry. Thus, carrying over the formulae for convolution of normal random variables allows the simple explicit equation to be written down, resulting in (5.6). But, $x_t^2 + y_t^2 = T^2$ is the radial distance from the

$$P_{damage \mid (x_t, y_t)} = \frac{b^2}{b^2 + \sigma_p^2}\, e^{-\frac{1}{2}\frac{(x_t^2 + y_t^2)}{(b^2 + \sigma_p^2)}} \qquad (5.6)$$

actual aim point to the target center located at (x_t, y_t). Substitution of T provides (5.7). It is assumed that each

$$P_{damage \mid T} = \frac{b^2}{b^2 + \sigma_p^2}\, e^{-\frac{1}{2}\frac{T^2}{b^2 + \sigma_p^2}} \qquad (5.7)$$

penetrator has an identically distributed, equally likely probability of damaging the target. Therefore, the probability that n penetrators cause no damage given the

actual target center at (x_t, y_t) is given by (5.8). The

$$P_{no\ damage\ |\ T} = \left(1 - \frac{b^2}{b^2+\sigma_p^2}\, e^{-\frac{1}{2}\frac{T^2}{b^2+\sigma_b^2}} \right)^n \tag{5.8}$$

unconditional probability of no damage is calculated by multiplying the conditional probability by the radial miss distance distribution and integrating over the range of radial miss errors. Again, $T^2 \div D^2\sigma^2$ is distributed as a Chi-square random variable with two degrees of freedom.

$$P_{no\ damage} = \int_0^\infty \left(1 - \frac{b^2}{b^2 + \sigma_p^2}\, e^{\frac{-T^2}{b^2 + \sigma_p^2}} \right)^n e^{-\frac{\frac{1}{2}T^2}{D^2\sigma_\alpha^2}}\, \frac{1}{2} d\left(\frac{T^2}{D^2\sigma_\alpha^2}\right) \tag{5.9}$$

The binomial series expansion for a factor raised to the n^{th} power is as given in (5.10). The conditional probability

$$(a + b)^n = \sum_{j=0}^{n} \binom{n}{j} a^j\, b^{n-j} = \sum_{j=0}^{n} \binom{n}{j} b^j\, a^{n-j} \tag{5.10}$$

of no damage raised to the power n may be replaced by its binomial series expansion. This, combined with a convenient change of variable, where $w = \frac{1}{2}T^2$, yields (5.11).

$$P_{no\ damage} = \int_0^\infty \sum_{j=0}^{n} \binom{n}{j} \left(\frac{-b^2}{b^2 + \sigma_p^2}\, e^{\frac{-w}{b^2 + \sigma_p^2}} \right)^j \frac{e^{\frac{-w}{D^2\sigma_\alpha^2}}}{D^2\sigma_\alpha^2}\, dw \tag{5.11}$$

Rearrangement of summation and integration terms is given in (5.12) and completion of the integration yields the

$$P_{no\ damage} =$$
$$\sum_{j=0}^{n} \binom{n}{j} \left(\frac{-b^2}{b^2 + \sigma_p^2}\right)^j \left(\frac{1}{D^2\sigma_\alpha^2}\right) \int_0^\infty e^{-w\left(\frac{j}{b^2+\sigma_p^2} + \frac{1}{D^2\sigma_\alpha^2}\right)} dw \quad (5.12)$$

probability that the target is undamaged, given by (5.13).

$$P_{no\ damage} = \sum_{j=0}^{n} \binom{n}{j} \left(\frac{-b^2}{b^2 + \sigma_p^2}\right)^j \left(\frac{b^2+\sigma_p^2}{jD^2\sigma_\alpha^2 + b^2 + \sigma_p^2}\right) \quad (5.13)$$

The probability that the target is damaged by one or more penetrators is given by $P_{at\ least\ one\ hit} = 1 - P_{no\ damage}$, as in (5.14).

$$P_{\geq 1\ hit} = 1 - \sum_{j=0}^{n} \binom{n}{j} \left(\frac{-b^2}{b^2 + \sigma_p^2}\right)^j \left(\frac{b^2+\sigma_p^2}{jD^2\sigma_\alpha^2 + b^2 + \sigma_p^2}\right) \quad (5.14)$$

D. OPTIMAL DETONATION DISTANCE

Parameters $b = r_v \div \sqrt{2}$ and $\sigma_\alpha = 5$ milliradians have been determined previously based on convention and the engagement geometry. The only parameter which depends on detonation distance is the bivariate standard deviation of penetrator spread, σ_p. It is reasonable to assume that the penetrator spray cone will be fairly well-defined. It is likely that most of the penetrators will fall within the circular cookie-cutter penetrator disk area, determined by $z\tan\phi$. Thus, it is reasonable to assume that two standard deviations of penetrator spray equal the cookie-cutter penetrator spray radius; $2\sigma_p = z\tan\phi$ or $\sigma_p = \frac{1}{2}z\tan\phi$. Substitution for parameters b, σ_α^2, and σ_p in the equation for probability of

damage from n penetrators yields (5.15). This equation may be

$$P_{\geq 1\,hit} = 1 - \sum_{j=0}^{n} \binom{n}{j} \left(\frac{\frac{-r_v^2}{2}}{\frac{r_v^2}{2} + \frac{z^2 \tan^2\phi}{4}} \right)^j \left(\frac{\frac{r_v^2}{2} + \frac{z^2 \tan^2\phi}{4}}{jD^2\sigma_\alpha^2 + \frac{r_v^2}{2} + \frac{z^2 \tan^2\phi}{4}} \right) \qquad (5.15)$$

maximized with respect to detonation distance z. A closed form solution for optimal detonation distance has not been found. However, plotting probability of kill at a given engagement range as a function of detonation distance reveals the maximum probability of damage and the optimal detonation distance for a given engagement. Figure 13 displays the probability of kill as a function of detonation distance for the hypothetical weapon described in the previous chapter. Engagement of a UAV with a 5 m² vulnerable area is considered.

E. COMPARISON TO COOKIE-CUTTER DAMAGE MODEL

It is expected that the cookie-cutter and diffuse Gaussian models should provide similar results if the penetrator spray bivariate normal variance is chosen such that most of the penetrators are located within the deterministic circular spray area of the cookie-cutter model. These models should be roughly equivalent if the diffuse penetrator spray deviation is selected such that twice the deviation is equal to the cookie-cutter uniform spray radius. Under this condition, almost 96 percent of the penetrators are expected to be located within the circular cookie-cutter spray area. Figure

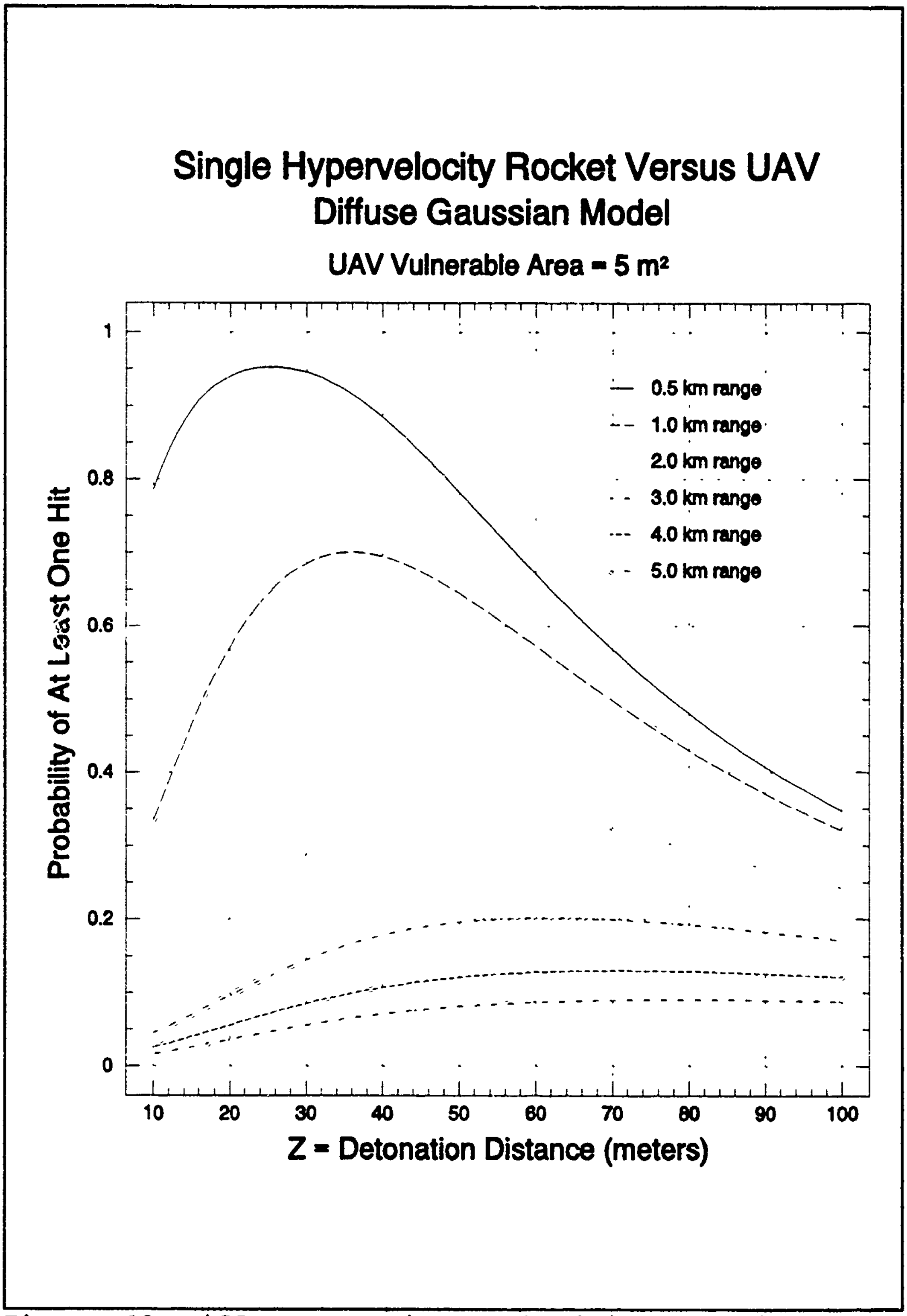

Figure 13 Diffuse Gaussian Probability of Kill as a Function of Detonation Distance

14 shows a comparison of results from the two models for a 1.0 kilometer engagement range. The two models provide almost identical results for maximum probability of kill and optimal detonation distance. Table IV shows a comparison of results for the hypothetical engagements analyzed.

TABLE IV COMPARISON OF MODEL RESULTS

UAV Area (m^2)	UAV Range (km)	Cookie Cutter P_{damage}	Cookie Cutter Optimal z (m)	Diffused Gaussian P_{damage}	Diffused Gaussian Optimal z (m)
5	5	0.090	79	0.090	79
4	5	0.075	74	0.075	75
3	5	0.058	69	0.058	70
2	5	0.041	63	0.041	63
5	4	0.130	70	0.130	71
4	4	0.108	67	0.109	67
3	4	0.086	62	0.086	62
2	4	0.061	56	0.061	56
5	3	0.201	61	0.202	61
4	3	0.171	58	0.171	58
3	3	0.137	54	0.137	54
2	3	0.098	48	0.099	49
5	2	0.349	50	0.351	50
4	2	0.303	47	0.304	48
3	2	0.250	44	0.240	44
2	2	0.186	40	0.187	40
5	1	0.695	35	0.701	36
4	1	0.638	33	0.643	34
3	1	0.563	31	0.567	32
2	1	0.459	28	0.462	28
5	0.5	0.946	25	0.953	26
4	0.5	0.921	24	0.929	24
3	0.5	0.880	22	0.888	22
2	0.5	0.804	20	0.812	20

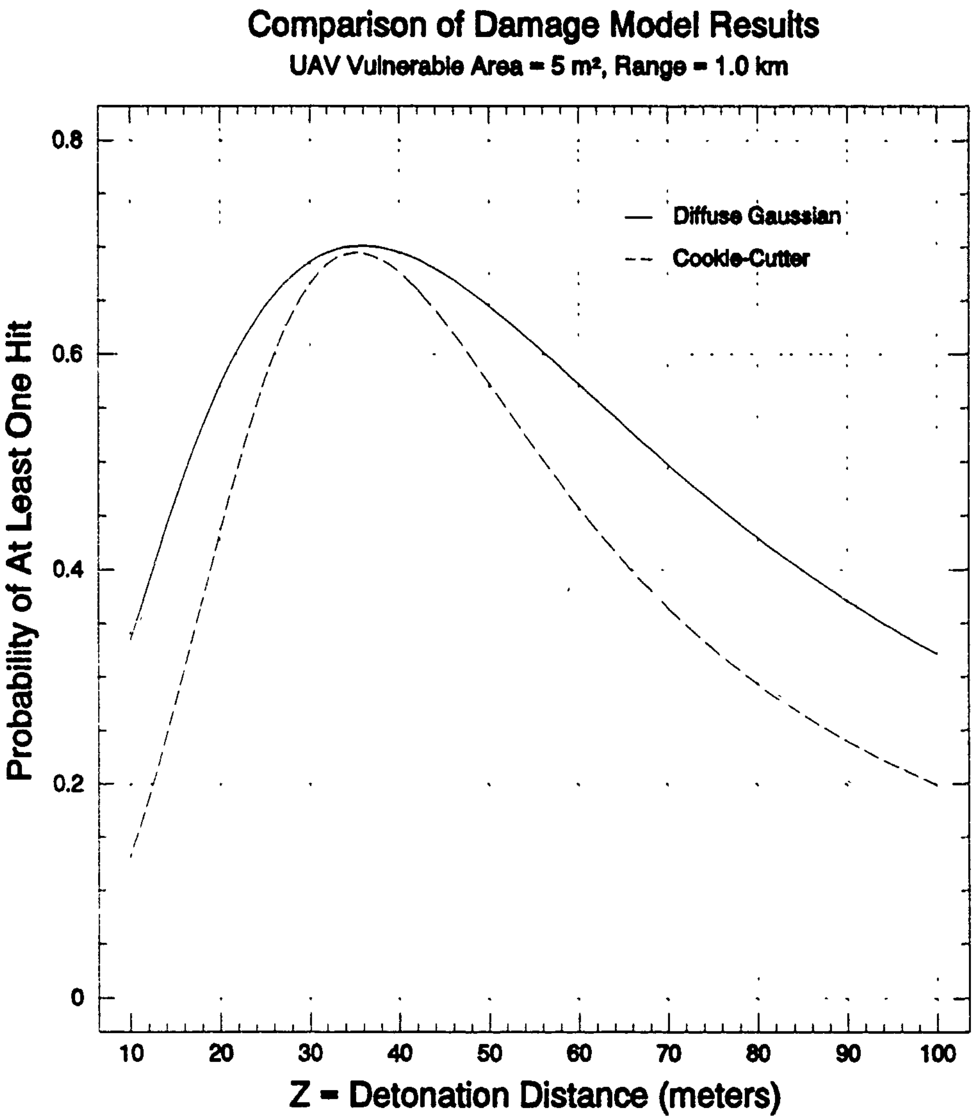

Figure 14 Model Comparison: Maximum Probability of Kill and Optimal Detonation Distance

As expected, the diffuse Gaussian model provides higher probabilities of kill for detonation distances other than the optimal detonation distance. This occurs because all penetrators have some non-zero probability of damage in the diffuse target model. Penetrators which impact outside the circular vulnerable area have zero probability of damage in the cookie-cutter target model. However, both models show virtually the same optimal detonation distance which maximizes the probability of killing the UAV.

F. SENSITIVITY ANALYSIS

As was true for the cookie-cutter model, the diffuse Gaussian model is relatively insensitive to target vulnerable area estimate error for long range engagements. However, the diffuse Gaussian model is less sensitive to vulnerable area estimate error than is the cookie-cutter endgame model, especially for short range UAV engagements. The diffuse Gaussian model shows only half of the percent probability of kill degradation that the cookie-cutter model does for a 0.5 kilometer engagement range (Figure 15). Figures 16 and 17 compare the two models at engagement ranges of 3 and 0.5 kilometers respectively. Live fire experiments might be conducted and examined to determine which model most realistically characterizes the sensitivity to UAV vulnerable area estimate error.

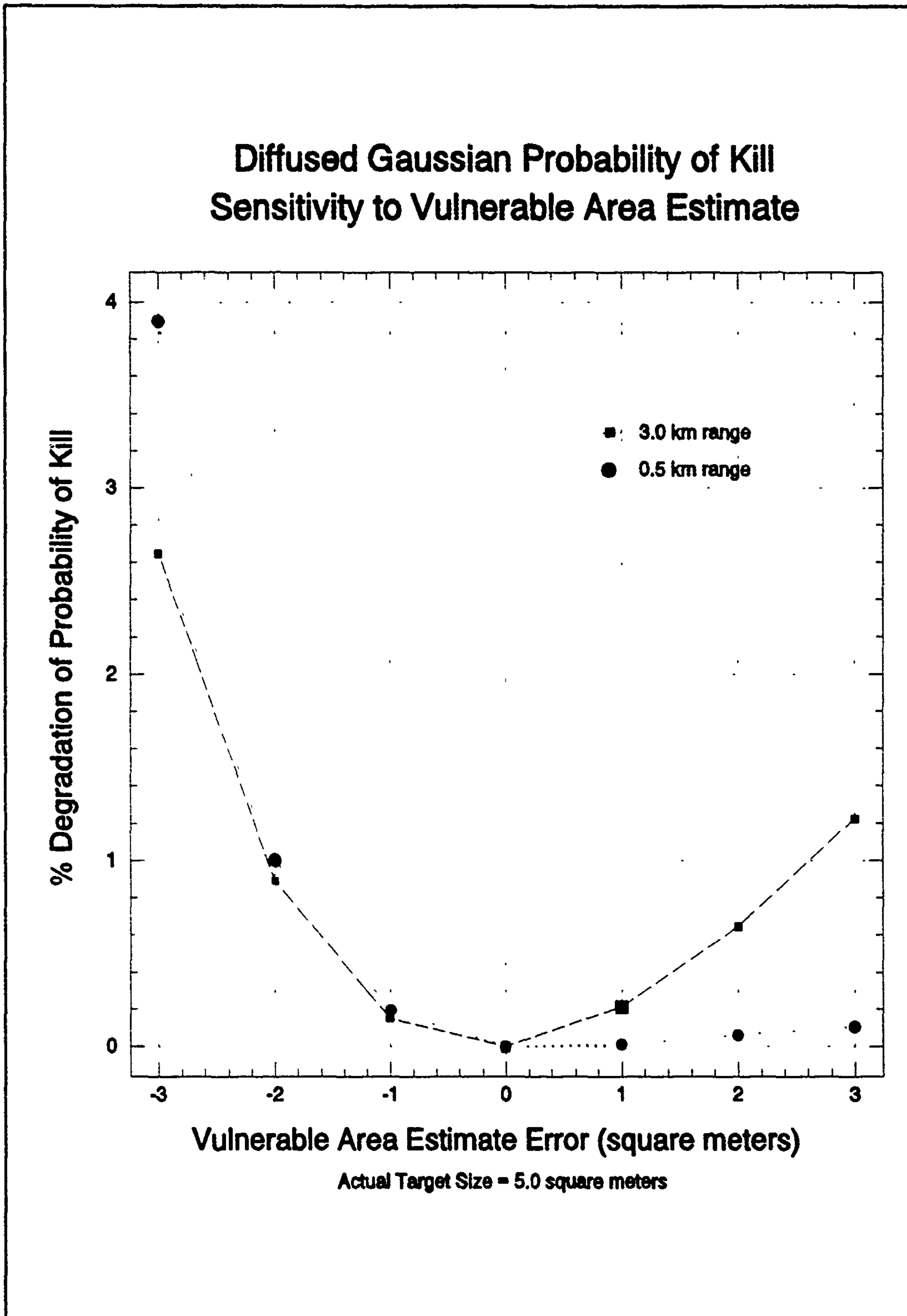

Figure 15 Diffused Gaussian Model Sensitivity to UAV Vulnerable Area Estimate Error

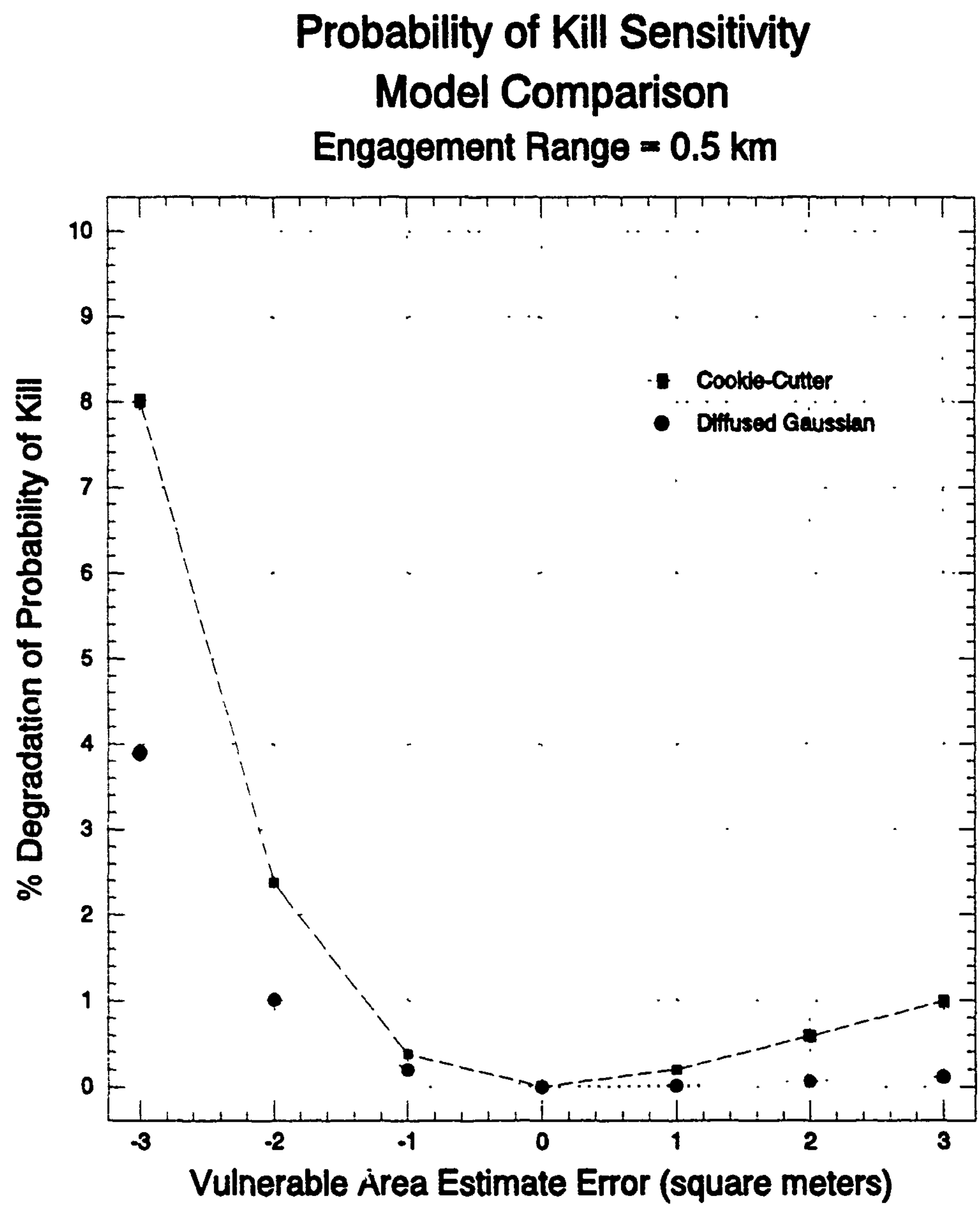

Figure 16 Model Sensitivity Comparison (0.5 km)

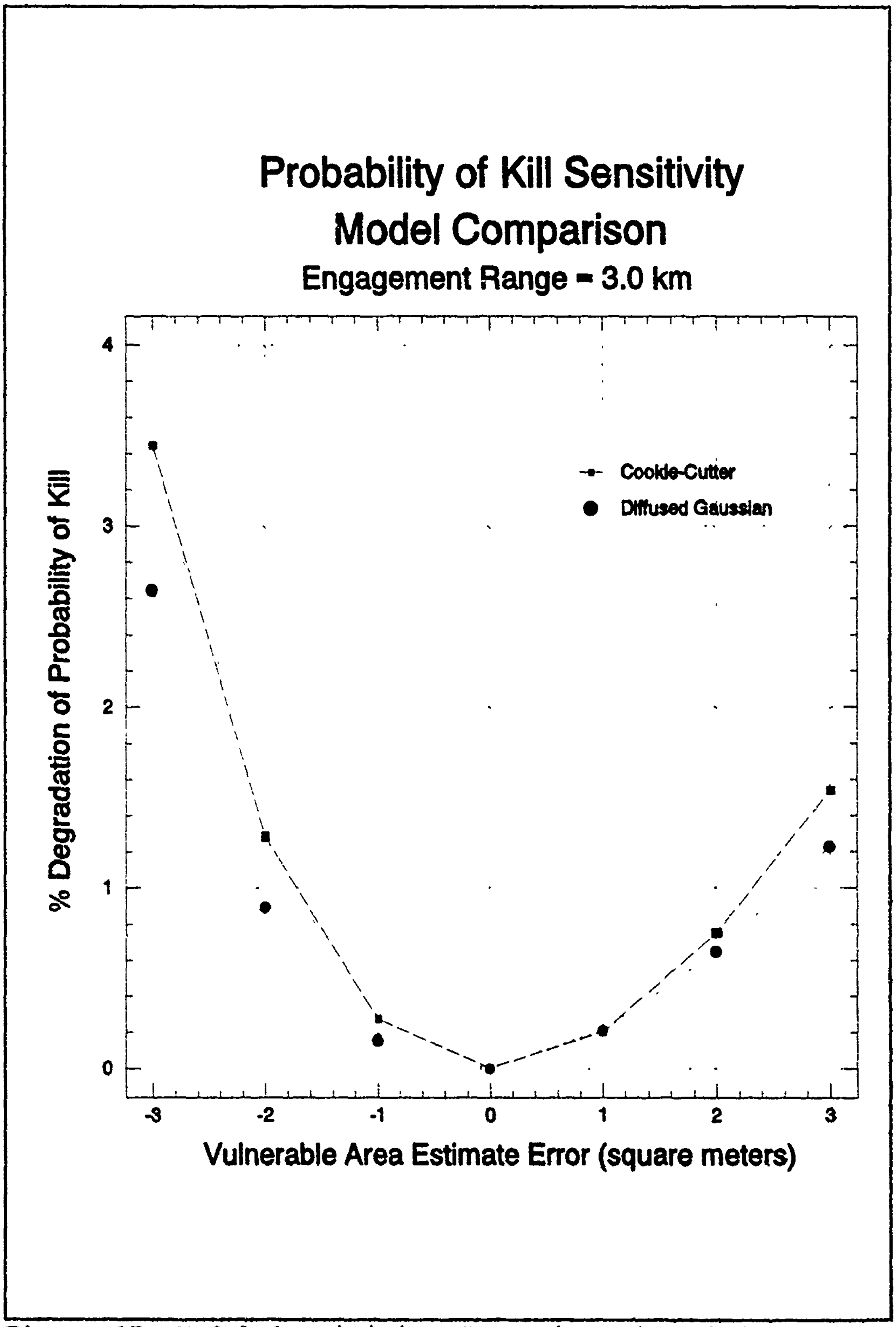

Figure 17 Model Sensitivity Comparison (3.0 km)

G. PENETRATOR DISPERSION PARAMETER SELECTION

The penetrator dispersion parameter, σ_p, was set to $\frac{1}{2}(z\tan\phi)$ to make the two models roughly equivalent for validation of the diffuse Gaussian model. However, the dispersion of the penetrator spray may be somewhat controllable by changing the rocket design. For this reason, other values for the dispersion parameter were analyzed to allow comparison. Results for dispersion deviations of $\frac{1}{4}(z\tan\phi)$, $\frac{1}{2}(z\tan\phi)$, and $(z\tan\phi)$ reveal that there is an absolute maximum probability of damage attainable for a given engagement. It also shows that optimal detonation distance decreases as dispersion increases. In fact, optimal detonation distance is linearly proportional to the inverse of dispersion deviation.

This relationship highlights the importance of careful selection of penetrator spray cone half-angle. Dispersion deviation depends on the tangent of this angle as well as detonation distance. Controlled selection of spray cone half-angle will ensure that the optimal detonation distance is small enough so that the penetrators have enough energy to sufficiently damage the UAV on impact. As penetrators travel farther, aerodynamic drag may excessively reduce their kinetic energy.

It is important to note that the detonation distance is also constrained by the maximum distance which the flechette

penetrators can travel after detonation and still maintain kinetic energy sufficient to kill the target. This constraint is not considered in this analysis. If the optimal detonation distance predicted by these models exceeds this kinetic limitation of the penetrators, the detonation distance should be chosen to ensure that sufficient energy is retained to kill the target. This constraint is a function of rocket design and target vulnerability.

VI. CONCLUSIONS

A. UAVS ARE A THREAT TO GROUND FORCES

UAVs are an important asset to battlefield commanders. They provide timely reconnaissance information and targeting data. Lethal UAVs also serve as force multipliers by supplementing and complementing manned aircraft. These factors make UAVs such a desirable asset that U.S. forces are likely to face hostile UAVs in future conflicts. U.S. surface forces must be able to efficiently defeat hostile UAVs in order to maintain tactical advantage in a conflict.

Since UAVs are a threat to U.S. forces, troops should be trained to detect and identify them. U.S. personnel should become familiar with enemy UAV appearances, capabilities, and tactics. It is essential to understand how and why UAVs are employed. Both ground troops and naval units should become familiar with the anti-UAV capabilities of their weapons so they may make efficient use of resources in combating UAVs. This will also reveal strengths and deficiencies of existing systems in an anti-UAV role. Evaluation of current systems will also help to determine whether new systems are required to provide an adequate anti-UAV capability.

B. TOOLS FOR HYPERVELOCITY ROCKET LETHALITY ASSESSMENT

Hypervelocity rockets promise to provide a viable anti-UAV weapon. Probability models of the lethal air defense endgame provide a means of predicting the lethality of hypervelocity rockets for various engagement scenarios. The measure of effectiveness considered in this analysis is the probability that one or more flechette penetrators, from a single rocket, hit the UAV vulnerable area. It is assumed that a single penetrator hit to the UAV vulnerable area will kill the target. These models may easily be adapted to study weapons which have a probability of kill given hit less than one which would require multiple hits to destroy the target with acceptable confidence. Both models allow determination of the optimal detonation distance, which provides this maximum probability of killing the UAV.

A cookie-cutter damage probability model was first used to describe the air defense endgame with simplifying assumptions. A diffused Gaussian damage model was then used to provide a more realistic representation of the endgame. The models provide similar results for targets with small, concentrated vulnerable areas. However, the diffused Gaussian model more realistically models targets which have less concentrated vulnerable components. These models may be used to design an effective anti-UAV hypervelocity rocket weapon and compare weapon lethality to that of guns and missiles.

It is shown that controlled selection of the detonation distance of the rocket may significantly improve anti-UAV effectiveness. The analysis in this thesis provides the basis for developing an optimal fuzing algorithm which determines the appropriate fuzing time delay to provide the optimal detonation distance for a given scenario.

Sensitivity analysis shows that is beneficial to overestimate the UAV vulnerable area to provide a more robust fuzing algorithm. Underestimating the UAV vulnerable area provides significant degradation of the anti-UAV effectiveness. UAV vulnerable areas are extremely aspect dependent, for most UAVs the front and rear of the vehicle present very small vulnerable areas, the sides present larger vulnerable areas, and the top and bottom provide the largest vulnerable areas. Rocket fuzing should be based on vulnerable areas corresponding to one of the larger aspects, side or bottom, which will likely be presented to the rocket. Basing rocket fuzing on frontal or rear vulnerable areas may significantly reduce the probability of destroying the UAV from the maximum probability of kill attained with perfect vulnerable area estimation.

C. FURTHER ANALYSIS

Data from UAV signature measurements and live-fire experiments may be used to determine realistic parameters for the models presented in this thesis. This will allow use of

the models in simulations to further study the lethality of hypervelocity rockets.

The possibility of steering penetrator spray from missiles is currently being researched. This capability would increase the lethality of these weapons since the destructive energy of the damage mechanisms would be focused on the target. It may also be beneficial to develop a capability to steer the hypervelocity rocket penetrator spray directly toward the target. Further analysis may be appropriate to determine the feasibility and payoff of such a modification.

APPENDIX A COOKIE-CUTTER MODEL APL COMPUTER PROGRAM

```
 X←COOKIE
⍝ PROGRAMMER: LT JOSEPH J. BEEL, USN
⍝ US NAVAL POSTGRADUATE SCHOOL
⍝ JANUARY 1992
⍝
⍝ THIS PROGRAM COMPUTES THE PROBABILITY THAT AT LEAST ONE
⍝ FLECHETTE PENETRATOR FROM A HYPERVELOCITY ROCKET HITS
⍝ THE TARGET VULNERABLE AREA AS BASED ON A COOKIE-CUTTER MODEL OF THE
⍝ TARGET AS MODELED IN CHAPTER IV OF THIS THESIS
⍝
⍝ OUTPUT MATRIX IS INITIALIZED FOR DATA STORAGE
 X←3 91⍴0
⍝
⍝ DETONATION DISTANCE IS VARIED FROM 10 TO 100 METERS
 Z←9+⍳91
⍝
⍝ DATA INPUT
⍝ USER MUST INPUT:
⍝                  TARGET VULNERABLE AREA  (SQUARE METERS)
⍝                  DISPERSION CONE HALF ANGLE (DEGREES)
⍝                  NUMBER OF FLECHETTES PER ROCKET
⍝                  TARGET RANGE WHEN ENGAGED (KILOMETERS)
⍝                  ANGULAR DELIVERY ERROR (MILLIRADIANS)
⍝
INPUT:'********** DATA INPUT **********'
 'INPUT THE TARGET VULNERABLE AREA (SQUARE METERS)'
 VULAREA←⎕
 'INPUT THE DISPERSION CONE HALF ANGLE IN DEGREES'
 PHID←⎕
 'INPUT THE NUMBER OF FLECHETTES PER PROJECTILE'
 N←⎕
 'INPUT THE RANGE TO TARGET WHEN ENGAGED BY GUN (KM)'
 RANGE←⎕
 'INPUT THE ANGULAR FIRE CONTROL STANDARD DEVIATION (MILLIRADIANS)'
 ALPHAMR←⎕
 '     '
⍝
⍝ DATA ECHO
 ⎕←'THE FOLLOWING DATA HAS BEEN INPUT:'
 ⎕←'TARGET RANGE                        = ',(⍕RANGE),' KM'
 ⎕←'VULNERABLE AREA                     = ',(⍕VULAREA),' SQUARE METERS'
 ⎕←'DISPERSION HALF ANGLE               = ',(⍕PHID),' DEGREES'
 ⎕←'ANGULAR MISS STANDARD DEVIATION     = ',(⍕ALPHAMR),' MILLIRADIANS'
 ⎕←'NUMBER OF FLECHETTES PER PROJECTILE = ',(⍕N)
 ⎕←'     '
⍝
⍝ DATA VERIFICATION
 ⎕←'IF THIS DATA IS INCORRECT, TYPE ''0'''
 ⎕←'      IF CORRECT, TYPE ''1'''
 ANSWER←⎕
 →(ANSWER≠1)/INPUT
⍝
```

```
⍝ CALCULATION OF VULNERABLE AREA RADIUS (ASSUMED CIRCULAR)
 RV←(VULAREA÷(○1))*0.5
 ⎕←'VULNERABLE RADIUS                              = ',(⍕RV),' METERS.'
⍝
⍝ CONVERSION OF DISPERSION CONE HALF ANGLE TO RADIANS
⍝
 PHI←(PHID÷180)×(○1)
⍝
⍝ CONVERSION OF ANGULAR DEVIATION FROM MILLIRADIANS TO RADIANS
 ALPHA←ALPHAMR÷1000
 DIST←RANGE×1000
⍝
⍝ CALCULATION OF RADIAL MISS DEVIATION
 SIGMA←DIST×ALPHA
 ⎕←'RADIAL MISS DEVIATION = ',(⍕SIGMA),' M AT A RANGE OF ',(⍕RANGE),'K
⍝
⍝ CALCULATION OF CONSTANTS C1 AND C2
 C1←(3○PHI)*2
 C2←C1÷(SIGMA*2)
⍝
⍝ CALCUALTION OF PROBABILITIES P1 AND P2
⍝ P1 = PROBABILITY THAT PENETRATOR DISK COVERS TARGET AREA
⍝ P2 = PROBABILITY THAT PENETRATOR DISK MISSES TARGET AREA
⍝ P1 + P2 = 1, IE. MUTUALLY EXCLUSIVE AND EXHAUSTIVE
 P2←*(¯0.5×C2×(Z*2))
 P1←1-P2
⍝
⍝ CALCULATION OF PROBABILITY THAT NO PENETRATORS HIT TARGET
⍝ GIVEN THAT PENETRATOR DISK OVERLAPS TARGET
⍝ NUMBER TO HIT TARGET IS BINOMIAL WITH PROBABILITY RHO
⍝
⍝ RHO IS SET TO 1 WHEN RV ≥ RP
 RHO←(((RV*2)÷(C1×(Z*2)))×((RV*2)<(C1×(Z*2))))+((RV*2)≥(C1×(Z*2)))
 P0←(1-RHO)*N
⍝
⍝ PROBABILITY OF AT LEAST ONE HIT EQUALS 1-P(NO HITS)
⍝ CALCUALTION OF PROBABILITY OF AT LEAST ONE HIT
 PHIT←1-(P2+(P1×P0))
⍝
⍝ CALCULATION OF DERIVATIVE OF PROBABILITY WRT DETONATION DISTANCE
 PPRIME←(C2×Z×P2)-(((C2×Z×P2)×P0)+N×((P0*(÷N))*(N-1))×2×(RV*2)×P1÷(C1×
⍝
⍝ ASSIGNMENT OF OUTPUT TO X MATRIX
 X[1;]←Z
 X[2;]←PHIT
 X[3;]←PPRIME
 ⎕←'   '
⍝
⍝ CALCULATION OF MAXIMUM PROBABILITY OF ≥ 1 PENETRATOR HIT
 PMAX←PHIT[1↑⍒PHIT]
⍝
⍝ CALCULATION OF DETONATION DISTANCE GIVING MAXIMUM P(≥1 HIT)
```

```
[104]  ⍝ THUS, ZMAX IS OPTIMAL DETONATION DISTANCE
[105]   ZMAX←Z[1↑⍒PHIT]
[106]   ⎕←'MAXIMUM PROBABILITY OF ≥ 1 HIT =',(⍕PMAX),'AT Z = ',(⍕ZMAX),'METERS.'
[107]  ⍝
[108]  ⍝ CALCULATION OF PENETRATOR DISK RADIUS AT TARGET RANGE
[109]   ⎕←'PROJECTILE RADIUS = ',(⍕(ZMAX×(C1*0.5))),' METERS.'
```

APPENDIX B GAMS NON-LINEAR OPTIMIZATION PROGRAM

```
*-----GAMS AND DOLLAR CONTROL OPTIONS---------------
*             (SEE APPENDICES B & C)

OPTIONS
     LIMCOL = 0     , LIMROW =   0    , SOLPRINT =  OFF,
     DECIMALS = 4   , RESLIM = 100    ,
     OPTCR    = 0.0 , SEED     = 3141 ;

*-----DEFINITIONS AND DATA-------------------------

     SCALARS
*---------------- DATA CONTROLLED BY USER-----------

          RANGE     RANGE TO TARGET              /1.0/
          AV        TGT VULNERABLE AREA SQ METERS  /5.0/
          SIGMAA    ANGULAR DELIVERY ERROR  MR /5.0/
          PHI       DISPERSION CONE HALF ANGLE /15.0/
          N         NUMBER OF PENETRATORS      /100/


*-------------------------------------------------------------

          PI        CONSTANT PI    /3.141592654/      ;

     PARAMETERS
          RV
          SIGMAT
          C1
          C2  ;

          RV = SQRT(AV/PI);

          SIGMAT = RANGE *SIGMAA;

          C1 =   (SIN(PHI*PI/180)/COS(PHI*PI/180))**2;

          C2 = C1 / (SIGMAT**2);

*----------------MODEL-------------------------------------

     POSITIVE VARIABLES
       Z  DETONATION DISTANCE
       P1 PROBABILITY PENETRATORS COVER TARGET
       P2 PROBABILITY PENETRATORS DO NOT COVER TARGET
       P0 PROBABILITY NO HITS IF PENETRATORS COVER TARGET   ;


     VARIABLE
       PKILL  PROBABILITY THAT THE TARGET IS KILLED;

```

```
       Z.LO = 1.0 SET LOWEST DETONATION DISTANCE TO ONE METER  ;

     EQUATIONS
       OBJ            PROBABILITY OF KILL
       PROB1          CALCULATE P1
       PROB2          CALCULATE P2
       PROB0          CALCULATE P0
       A              ENSURE PKILL IS A PROBABILITY ;

 * MAXIMIZE
     OBJ..     PKILL =E= 1   - P2   - (P1*P0**N)  ;

 * SUBJECT TO

     PROB1..      P1 =E= 1 - EXP(-0.5*(C2*Z**2)) ;
     PROB2..      P2 =E= EXP(-0.5*(C2*Z**2)) ;
     PROB0..      P0 =E= 1 - (RV**2/(C1*Z**2));

     A..          PKILL =L= 1.0 ;

   MODEL ROCKET /ALL/;
   SOLVE ROCKET USING  NLP MAXIMIZING PKILL;
 *------------------REPORTS----------------------------
 * ECHO DATA AND PRINT PARAMETERS
   DISPLAY RANGE,AV,SIGMAA,PHI,N,RV,SIGMAT,C1,C2;

 * PRINT THE OPTIMAL OBJECTIVE VALUE AND SOLUTION.
   DISPLAY Z.L, PKILL.L;
```

PARAMETERS

AV	TGT VULNERABLE AREA SQUARE METERS
C1	
C2	
N	NUMBER OF PENETRATORS
PHI	DISPERSION CONE HALF ANGLE
PI	CONSTANT PI
RANGE	RANGE TO TARGET
RV	
SIGMAA	ANGULAR DELIVERY ERROR MILLIRADIANS
SIGMAT	

VARIABLES

P0	PROBABILITY NO HITS IF PENETRATORS COVER TARGET
P1	PROBABILITY PENETRATORS COVER TARGET
P2	PROBABILITY PENETRATORS DO NOT COVER TARGET
PKILL	PROBABILITY THAT THE TARGET IS KILLED
Z	DETONATION DISTANCE

```
EQUATIONS

A           ENSURE PKILL IS A PROBABILITY
OBJ         PROBABILITY OF KILL
PROB0       CALCULATE P0
PROB1       CALCULATE P1
PROB2       CALCULATE P2


MODELS

ROCKET


COMPILATION TIME      =        0.074 MINUTES
MODEL STATISTICS     SOLVE ROCKET USING NLP FROM LINE 77

MODEL STATISTICS

BLOCKS OF EQUATIONS      5     SINGLE EQUATIONS       5
BLOCKS OF VARIABLES      5     SINGLE VARIABLES       5
NON ZERO ELEMENTS       11     NON LINEAR N-Z         5
DERIVATIVE POOL          5     CONSTANT POOL          6
CODE LENGTH            129

GENERATION TIME       =        0.065 MINUTES

EXECUTION TIME        =        0.158 MINUTES
SOLUTION REPORT      SOLVE ROCKET USING NLP FROM LINE 77


               S O L V E     S U M M A R Y

     MODEL   ROCKET               OBJECTIVE  PKILL
     TYPE    NLP                  DIRECTION  MAXIMIZE
     SOLVER  MINOS5               FROM LINE  77

**** SOLVER STATUS      1 NORMAL COMPLETION
**** MODEL STATUS       2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE                  0.6945

 RESOURCE USAGE, LIMIT          0.299      100.000
 ITERATION COUNT, LIMIT        28          1000
 EVALUATION ERRORS              0             0

     M I N O S    5.2    (Mar 1988)
     = = = = =
     B. A. Murtagh, University of New South Wales
       and
     P. E. Gill,  W. Murray,  M. A. Saunders and M. H. Wright
     Systems Optimization Laboratory, Stanford University.

 WORK SPACE NEEDED (ESTIMATE)    --     540 WORDS.
 WORK SPACE AVAILABLE            --   18622 WORDS.

 EXIT -- OPTIMAL SOLUTION FOUND
 MAJOR ITNS, LIMIT              21       50
 FUNOBJ, FUNCON CALLS            0       85
 SUPERBASICS                     1
 INTERPRETER USAGE             .05
 NORM RG / NORM PI      7.965E-10
```

```
**** REPORT SUMMARY :        0      NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
                             0      ERRORS

----      80 PARAMETER RANGE          =        1.0000 RANGE TO TARGET

             PARAMETER AV             =        5.0000 TGT VULNERABLE AREA
                          SQUARE METERS

             PARAMETER SIGMAA         =        5.0000 ANGULAR DELIVERY
                          ERROR MILLIRADIANS

             PARAMETER PHI            =       15.0000 DISPERSION CONE HALF
                          ANGLE

             PARAMETER N              =      100.0000 NUMBER OF
                          PENETRATORS

             PARAMETER RV             =        1.2616

             PARAMETER SIGMAT         =        5.0000

             PARAMETER C1             =        0.0718

             PARAMETER C2             =        0.0029

----      83 VARIABLE  Z.L            =       35.2592 DETONATION DISTANCE

             VARIABLE  PKILL.L        =        0.6945 PROBABILITY THAT THE
                          TARGET IS KILLED
```

APPENDIX C DIFFUSE GAUSSIAN MODEL APL COMPUTER PROGRAM

```
  X←GAUSSIAN
 ⍝ PROGRAMMER LT JOSEPH J. BEEL, USN
 ⍝ US NAVAL POSTGRADUATE SCHOOL
 ⍝ JANUARY 1992
 ⍝
 ⍝ THIS PROGRAM COMPUTES THE PROBABILITY THAT AT LEAST ONE
 ⍝ FLECHETTE PENETRATOR FROM A HYPERVELOCITY ROCKET HITS THE
 ⍝ TARGET VULNERABLE AREA AS BASED ON DIFFUSED GAUSSIAN MODELS
 ⍝ OF THE TARGET AND PENETRATOR SPRAY.  CHAPTER V OF THIS THESIS.
 ⍝
 ⍝ DATA INPUT
 ⍝ USER MUST INPUT:
 ⍝                    TARGET VULNERABLE AREA (SQUARE METERS)
 ⍝                    DISPERSION CONE HALF ANGLE (DEGREES)
 ⍝                    NUMBER OF FLECHETTES PER ROCKET
 ⍝                    TARGET RANGE WHEN ENGAGED (KILOMETERS)
 ⍝                    ANGULAR DELIVERY ERROR DEVIATION (MILLIRADIANS)
 ⍝
 INPUT:'********** DATA INPUT **********'
  ⎕←'INPUT THE NUMBER OF FLECHETTES PER ROCKET.'
  N←⎕
  PHZ←100ρ0
  ⎕←'INPUT THE RANGE AT WHICH TARGET IS ENGAGED (KM).'
  R←⎕
 ⍝
 ⍝ CONVERSION OF ENGAGEMENT RANGE TO METERS
  RANGE←R×1000
  ⎕←'INPUT THE UAV VULNERABLE AREA (SQUARE METERS).'
  AV←⎕
 ⍝
 ⍝ CALCULATION OF VULNERABLE RADIUS BASED ON CIRCULAR AREA
  RV←(AV÷(○1))*0.5
 ⍝
 ⍝ COMPUTATION OF PARAMETER B
  B←RV÷(2*0.5)
  ⎕←'INPUT THE PENETRATOR SPRAY CONE HALF ANGLE (DEGREES).'
  PHID←⎕
 ⍝
 ⍝ CONVERSION OF PHI TO RADIANS
  PHI←(PHID×(○1))÷180
  ⎕←'INPUT THE STANDARD DEVIATION OF ANGULAR ERROR (MILLIRADIANS).'
  ALFAMR←⎕
 ⍝
 ⍝ DATA ECHO
  ⎕←'  '
  ⎕←'THE FOLLOWING DATA HAS BEEN INPUT:'
  ⎕←'TARGET RANGE                    = ',(⍕R),' KM'
  ⎕←'VULNERABLE AREA                 = ',(⍕AV),' SQUARE METERS'
  ⎕←'DISPERSION HALF ANGLE           = ',(⍕PHID),' DEGREES'
  ⎕←'ANGULAR MISS STANDARD DEVIATION = ',(⍕ALFAMR),' MILLIRADIANS'
  ⎕←'NUMBER OF FLECHETTES PER ROCKET = ',(⍕N)
  ⎕←'  '
```

```
⍝
⍝ DATA VERIFICATION
 ⎕←'IF THIS DATA IS INCORRECT TYPE ''0'''
 ⎕←'      IF CORRECT, TYPE ''1'''
 ANSWER←⎕
 →(ANSWER≠1)/INPUT
⍝
⍝ CONVERSION OF ANGULAR DEVIATION TO RADIANS
 SIGMAA←ALFAMR÷1000
⍝
⍝ CALCULATION OF RADIAL MISS DISTANCE DEVIATION
 SIGMAT←RANGE×SIGMAA
⍝
⍝ INITIALIZATION OF MINIMUM Z VALUE, ZMAX, AND PMAX
 Z←9
 PMAX←0
 ZMAX←0
⍝
⍝ LOOP TO VARY DETONATION DISTANCE Z FROM 9 TO 100 METERS
L1:Z←Z+1
⍝
⍝ CALCULATION OF PENETRATOR SPRAY DEVIATION
⍝ BASED ON DETONATION DISTANCE Z AND ANGLE PHI
 SIGMAP←Z×(3○PHI)÷2
⍝
⍝ ASSIGNMENT OF BINOMIAL PARAMETER J
 J←0,⍳N
⍝
⍝ COMPUTATION OF SUM B*2 + SIGMAP*2
 C1←(B*2)+(SIGMAP*2)
⍝
⍝ COMPUTATION OF BINOMIAL SERIES SUMMANDS
 SUMMAND←(J!N)×(((¯1×(B*2))÷C1)*J)×C1÷((J×(SIGMAT*2))+C1)
⍝
⍝ COMPUTATION OF PROBABILITY OF NO PENETRATOR HITS
 PNGIVENZ←+/SUMMAND
⍝
⍝ COMPUTATION OF PROBABILITY OF AT LEAST ONE HIT
 PHGIVENZ←1-PNGIVENZ
⍝ STORAGE OF PROBABILITY OF DAMAGE CONDITIONED ON Z
 PHZ[Z]←PHGIVENZ
⍝
⍝ COMPUTATION OF MAXIMUM PROBABILITY OF AT LEAST ONE HIT
 PMAX←(PMAX×(PMAX>PHGIVENZ))+(PHGIVENZ×(PMAX≤PHGIVENZ))
⍝
⍝  COMPUTATION OF DETONATION DISTANCE ZMAX WHICH GIVES MAXIMUM
⍝        PROBABILITY OF AT LEAST ONE HIT
 ZMAX←(ZMAX×(PMAX>PHGIVENZ))+(Z×(PMAX≤PHGIVENZ))
⍝
⍝
⍝
⍝ STOPPING CONDITION FOR LOOP
```

```
 →(Z<100)/L1
⍝
⍝ OUTPUT
 ⎕←'MAXIMUM PROBABILITY OF ≥ 1 HIT = ',(⍕PMAX),' AT Z = ',(⍕ZMAX),'.'
 X←PHZ
```

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